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DETERMINATION OF MINIMUM DATA BASE REQUIREMENTS FOR PERFORMANCE TESTING WITH CSA F417-1985

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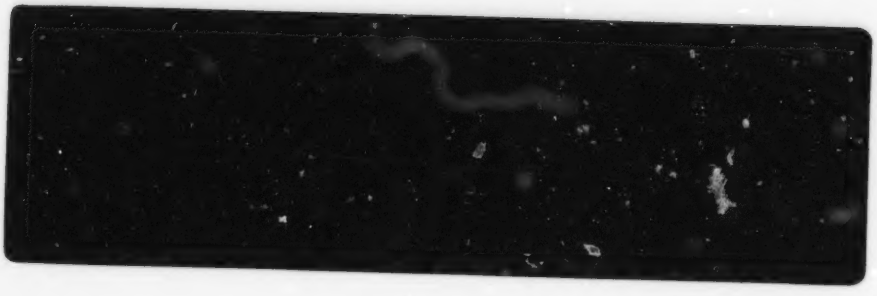

DETERMINATION OF MINIMUM DATA BASE REQUIREMENTS FOR PERFORMANCE TESTING WITH CSA F417-1985

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ABSTRACT

Field tests are the only practical and accurate method of determining the performance characteristics of a wind energy conversion system (WECS). The main purpose of these tests is to obtain a power curve or plot of (WECS) power output as a function of wind speed.

Power curves obtained from field tests have an element of statistical uncertainty which is carried over to any subsequent analysis using data from the power curve measurement. This report examines the potential sources of uncertainty and evaluates a proposed method of minimizing it. The report also makes specific proposals to alter the existing Canadian Standards Association (CSA) Preliminary Standard for Measurement (WECS) Performance F417-1986.

RÉSUMÉ

Les essais sur le terrain sont la seule méthode pratique et exacte de déterminer les particularités de fonctionnement d'un système de conversion de l'énergie éolienne (SCEE). Ces essais ont pour but principal d'obtenir une courbe ou un diagramme de la puissance du SCEE en fonction de la vitesse du vent.

Les courbes de puissance ainsi obtenues présentent un certain degré d'incertitude statistique, que l'on retrouve dans toute analyse subséquente effectuée à l'aide de ces données. Dans le présent rapport, on examine les sources éventuelles d'incertitude et on évalue une méthode proposée pour la minimiser. Les auteurs du rapport formulent également des propositions explicites visant à modifier les Normes préliminaires ACNOR F417-M1986 Système de conversion d'énergie éolienne (SCEE) - Performance.

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1. INTRODUCTION

Today's modern wind turbine technology has resulted from the concerted effort of designers in many western countries for nearly twenty years. In this time the operation, performance and reliability of equipment has improved substanstially. Economics have improved as well due both to these improvements and to significant cost reductions. Wind energy is now considered one of the most attractive of the renewable energy technologies in many areas where the wind resource is favourable and costs of other energy supply is high.

The development of the technology and industry has been paralleled by an increased interest in the development of standards for safety, design, installation, performance and other aspects of the wind turbine. These standards have been or are being developed on a national level by most countries and internationally.

Canada has participated in standards development at both levels, the Canadian Standards Association (CSA) with assistance from E.M.&R. has been managing the development of standards on solar and wind energy technologies since the early 1980's. A Technical Committee for standards on wind energy conversion systems (WECS) was formed and several sub-committees established to develop standards and guidelines in specific areas. One of the areas of interest has been performance testing of wind turbines. A Performance Sub-committee was formed and a preliminary standard was developed by the sub-committee over a period of several years. The sub-committee produced a preliminary standard in 1986 which was approved by the Technical Committee.

Prior to approval of a final standard the sub-committee and technical committee recommended that procedures prescribed in the standard be evaluated by carrying out a series of field trials.

During the fall and winter of 1986 three machines were tested. The results of the testing were inconclusive due to operational problems with the test machines and the observance of very high standard deviations of the output power measurements. For this

reason it was recommended that further field tests be conducted and a project commenced to test some additional machines. This report describes the results of testing of two additional machines.

2. BACKGROUND

2.1 PAST ACTIVITIES

The preliminary standard CSA F417(1986) is in many ways similar to those developed by the International Energy Agency (IEA) and the American Wind Energy Association (AWEA). There were however, several key differences, the most significant of which was the means of determination of the Minimum Data Base Requirement (MDBR), which defines the minimum amount of data necessary to accurately define the power curve. IEA and AWEA established somewhat arbitrary requirements to determine the minimum amount of data required. The CSA standard proposed a statistical analysis of the accumulated data within each wind speed bin[1] to determine if sufficient data had been obtained. It was felt that this analysis would give additional credibility to the results as well as shorten the time required to carry out a test.

When the preliminary standard was prepared a decision was made to carry out field tests on three machines using the standard to determine if the document in general and particularly the proposed method of determining minimum data requirements were practicable. The test machines were chosen to represent a range of WECS applications including both variable and fixed speed, vertical and horizontal axis and water pumping and electrical generation. The machines tested were located at the AWTS and the Lethbridge water pumping test station in Alberta and are described briefly below:

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[1]For example, using a bin width of 0.5 m/sec. would result in all data which was collected when the average wind speed was between say 8.25 and 8.75 m/sec. being allocated to the same 8.5 m/sec. bin for analysis. The test results are then averaged to give the average value of the dependent variable as a function of wind speed. The resulting power curve is a series of points along the power curve at equal increments of wind speed.

- Indal Technologies 7.5 kW vertical axis wind turbine, (VAWT) This machine is a constant speed grid connected VAWT at the Atlantic Wind Test Site.
- Bergey 1 kW, 120 volt DC, battery charging wind turbine. This is a passively pitched variable speed machine also.
- Bowjon airlift wind pump. This water pumping machine that was tested at the Lethbridge water pumper test site in Alberta.

Test results from these field tests suggested that the standards were generally adequate but identified several apparent problems with the proposed method of determining minimum data base requirements. The most apparent problem in all field tests was the difficulty to meet the minimum data base criteria. Standard deviations for all three tests failed to meet the criteria despite the fact that a large amount of data was obtained during the test period. Whether this was due to excessively stringent requirements on the part of the standard, peculiarities of the specific test machines or to unanticipated variation in the standard deviation of the power output was not known. A recommendation from these field tests was to further examine the sources of variation in the power curve and to recommend how the standard might be modified to overcome the problems.

2.2 TECHNICAL CONSIDERATIONS

The accurate determination of the power output of a wind turbine as a function of wind speed is most important. Accuracy of the power curve is essential since it is used to project the annual energy output (AEO) from a given machine. The AEO, determines the annual income generated by a machine and is necessary to carry out economic analysis on a potential project. Uncertainty in the determination of power output is reflected directly as uncertainty in the economic analysis.

Results from a large number of performance tests at AWTS in

addition to those conducted for this study have confirmed that there is a degree of uncertainty inherent in a wind turbine's power curve. These uncertainties can be reduced somewhat by careful planning but they cannot be eliminated. The stochastic nature of the determining parameters, statistical data analysis techniques used, instrumentation variations and the uncontrolled testing environment all contribute to the uncertainty. Any power curve derived from field tests will have a variation in power levels within the wind speed bin that the power levels are measured. These variations are usually indicated as standard deviations from the mean value of the samples within the wind speed bin.

There are many factors that will influence the power output of a wind turbine. The principal factors are:

(a) Machine effects - dirty blades
- yawing error
- control problems
- electro/mechanical deterioration
- rotor inertia

(b) Atmospheric effects - temperature
- rain/ice
- turbulence

(c) Instrument Effects - instrumentation and calibration error instrument response
- anemometer overspeeding
- anemometer location

(d) Terrain effects - turbulence
- vertical shear
- wind direction
- coherence of flow

(e) Statistical effects - averaging time
- errors in data
- bin width
- location and size of exclusion sector

Each of these may contribute to the variation in power output. Some of the effects of these factors can be eliminated by design of the test program but others cannot and will present themselves as deviation of the power curve.

In order to determine the quantity of data required to properly predict the power curve of a wind turbine the effect of each of these potential sources of variation within each bin must be considered.

3. TEST METHODOLOGY

The power curve for a wind turbine is obtained by simultaneously measuring the speed of the wind entering the turbine capture area and the power generated by the wind turbine. Since the wind at the instant it is acting on the turbine blades cannot be accurately measured it is estimated by an anemometer placed in a position where the windspeed it measures fairly represents the wind flowing into the turbine. The instantaneous values of wind speed and power are measured each second and than averaged over a longer period to reduce correlation differences resulting from spatial and temporal effects. The averages obtained are then sorted and categorized using a statistical technique called the method of bins. Using this technique all averages within a narrow range of wind speed, usually 0.5 m/sec., are grouped in a bin. The cumulative average, obtained over the test period, becomes the average values for that bin and provides one point on the power curve. The cumulative standard deviation of the power values in the bin is a measure of uncertainty and is the parameter of interest in this study.

If the testing is carried out over a very long period of time under similar conditions the cumulative average and standard deviation of the power output will eventually reach stable values within each bin of wind speed.

The goal of this test was to measure wind speed and power output for a long enough period to allow the average and standard deviation to reach stable values within each bin and then to analyze the data to determine how much data is required to reach those stable values. The study was scheduled to be carried out during the fall and winter months when wind speeds are highest. It was considered that this test period would easily provide enough data to make the necessary analysis.

The minimum data base tests were originally scheduled to be carried out on an Indal 35 kW vertical axis wind turbine located at the Atlantic Wind Test Site. Tests were disrupted as a result of gearbox problems with the unit and the tests were suspended for over a year until an alternate machine could be obtained. In October 1988 an Enertech E44/40 kW wind turbine was obtained and relocated to AWTS and instrumented for performance testing. Quantities measured were:

(1) power output,
(2) wind speed at equator height at three locations at increasing distances from the wind turbine,
(3) wind direction,
(4) temperature,
(5) barometric pressure, and
(6) relative humidity.

Power, wind speed and direction were measured at one hertz sample rates and averaged over one minute periods for the test. The other parameters were also measured at a one hertz sample rate and averaged over a ten minute period.

4. TEST DETAILS

4.1. TEST UNIT DESCRIPTION

The Enertech E44/40kw wind turbine is a production machine. About 300 are in use in wind farms in California.

The rotor consists of three wood epoxy blades mounted to a rigid hub which is connected through a two stage planetary gearbox to an induction generator. The rotor blades have fixed pitch. Power regulation in high winds is accomplished by aerodynamic stalling of the blades. The braking system consists of an electrodynamic brake working in conjunction with a spring applied parking brake on the generator shaft. Tip brakes are used to limit overspeeding in the event of normal brake failure. The rotor is down wind of the tower and the machine operates in free yaw.

4.2. INSTALLATION DETAILS

The machine is mounted on an 80 foot free standing lattice type tower near the northern end of the test site as illustrated in Figure 1.

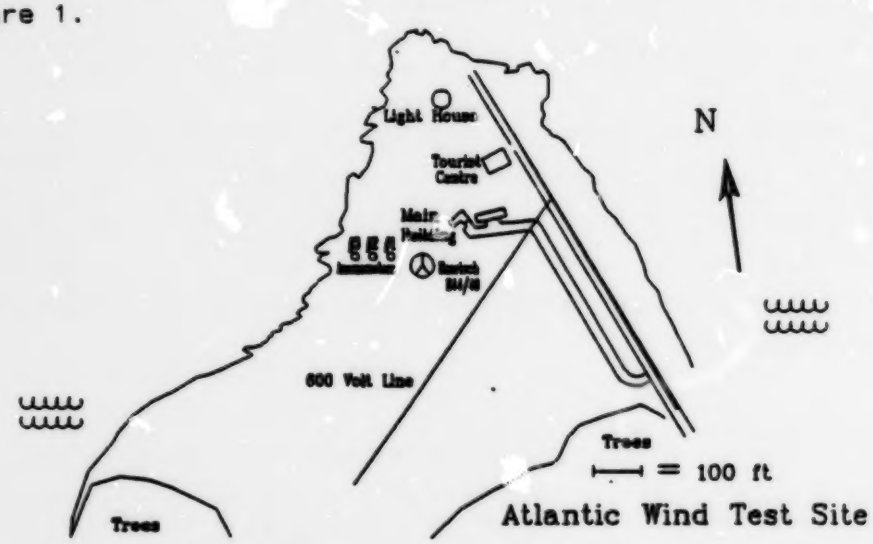

FIGURE 1

The three anemometer towers were erected in a north-westerly direction from the turbine at distances of 2.0, 4.0 and 5.8 rotor diameters or 27, 54 and 77 meters.

4.3. INSTRUMENTATION

Wind speeds were measured using Maximum model 45 anemometers. The Maximum has been found to have very good reliability, accuracy and precision. Calibration tests of twenty anemometers in a wind tunnel all indicated high repeatability of measurements. The rotating portion of the anemometer is molded in one piece from lexan plastic. The consistency of the mold and stability of lexan cause little variation in the dimensional or aerodynamic characteristics of the anemometers. The teflon bearings and 0.045" beryllium copper shaft are self lubricated and cause little drag. The small diameter of the shaft and the consistent coefficient of friction of the bearing material provides a bearing with relatively low and consistent losses.

Distance constant of the anemometer is 3 meters. Anemometer output is a sinosoidal signal produced by a rotating permanent magnetic and stationary pick up coil. The anemometer calibration constant is 0.06 Hz/mph.

The test anemometers were new and no calibration was carried out on them prior to the commencement of the test.

Power was measured by an F.W.Bell type PS-2301R 3 phase power transducer for the early part of the test and with a General Electric type 4711 transducer after problems were encountered with the original transducer.

4.4. DATA ACQUISITION/PROCESSING

Windspeed, power and direction were sampled at a one hertz rate and reduced to one minute average and standard deviation. The data was stored on a digital tape and then transferred to the AWTS main

data acquisition computer for processing. Temperature, barometric pressure, relative humidity and occurrence of icing events at the site meterological tower were also sampled at one hertz and averaged over ten minutes. The data was then combined in one file for the test period.

Data was collected for a period of about 70 days throughout September to November until the wind turbine suffered a brake failure and was taken out of service.

All data obtained was combined into a single file of one minute and ten minute averages. The file was then analyzed in several ways to determine the effects of the various potential sources of deviation and any erroneous data found was removed.

During the course of the test several problems were encountered with the power transducer which resulted in erroneous data being added to the bin file. In the first instance the power transducer output was clipped at high power rates. This problem was not detected until some time after operation was commenced and as a result several weeks of data in which the wind speed was above 9 m/sec. had to be rejected. In a later instance an underground cable connecting the power transducer to the data logger was severed. For several weeks this problem was intermittent. When he problem was discovered several weeks of intermittently bad data were accumulated. Considerable time was spent reviewing the entire database to identify and eliminate bad data. Unusual power levels within a bin and abnormally high or low deviations in power during a one minute average were the obvious events checked prior to removing data.

5. DISCUSSION OF TEST RESULTS

To examine the causes of deviation in a power curve it is necessary to consider all the potential factors and to eliminate, all those factors that have little significance.

In this analysis the effects of each of the variables on power deviation within each wind speed bin were examined. Initially two

bins (8.5 and 10.5 m/sec.) were examined in detail. The analysis showed consistent results between the two bins and confirmed that limitation of the analysis to these two bins should not overlook behaviour of the other bins as well.

Table 1 contains binned one minute averages of power output and standard deviation of the power output over the operating range of wind speeds. This data was obtained using anemometer #1 from a range of 270 degrees. It can be seen that a standard deviation of 2-3 kW exists over almost the entire operating range of the turbine.

TABLE 1

MINIMUM DATA BASE REQUIREMENTS TEST - 1989

ENERTECH BIN DISTRIBUTION - ONE MINUTE AVERAGES

ANEMOMETER # 1 - RANGE OF DIRECTION = 270 DEGREES

BIN AVERAGE WIND SPEED (M/SEC)	BIN COUNT	AVERAGE POWER (KW)	STANDARD DEVIATION (KW)
5	48	8	6.99
5.5	282	4.58	3.29
6	1658	4.51	2.37
6.5	3227	5.88	2.44
7	4399	8.38	2.73
7.5	4703	11.15	2.82
8	4645	14.19	2.74
8.5	4122	16.99	2.71
9	3211	19.6	2.93
9.5	1416	22.59	3.24
10	1063	25.65	3.3
10.5	992	28.28	3.31
11	958	30.74	3.25
11.5	892	33.19	3.09
12	895	35.15	2.87
12.5	906	36.6	2.48
13	796	37.94	2.24
13.5	747	39.03	2.13
14	730	40.08	2.07
14.5	666	40.92	1.81
15	490	41.46	.02
15.5	380	41.67	1.95
16	274	41.39	2.77
16.5	172	41.53	3.39
17	92	41.72	3.23
17.5	77	41.1	5.68
18	42	39.65	6.51

5.1. MACHINE EFFECTS

Any variation in power output due to machine effects can be detected by a degradation of the machine's performance over the period of the test. In this case no degradation was evident over the period of the test. Blade condition was monitored and no deterioration detected.

Errors attributable to yaw action can result if the rotor disc is not normal to the air flow throughout the averaging period. For free yaw machines a nonvertical yaw axis can cause yaw problems. There was no evidence that yaw action caused any problem during this test and the unit was noted to yaw properly in all direction of winds.

Variation or drifting of control system settings can cause substantial problems if set values of cut-in or cut-out wind speed are not stable. For this analysis the hysteresis problem that occurs at startup wind conditions was avoided by choosing wind speed bins between the upper and lower starting ranges. Hysteresis resulting from threshold levels inherent to the controls effects the extreme limits of operation but it is not evident throughout and is not of concern here.

5.2. INSTRUMENTATION EFFECTS

Instrumentation induced error is also a potential source of error over the term of a wind turbine test. Error is often introduced by mis-calibration or by calibration drift occurring on specific instruments. Wiring problems resulting from deterioration of exposed connections and noise pickup resulting from defective shielding and grounding are a less frequent but equally elusive problem.

Calibration drift is not often a problem with utility quality power transducers that are not exposed to ambient temperature variations that exceed stated limits. Since the instrumentation used in this test was located in a heated building it was considered there was no detectable drift of calibration.

Anemometer overspeeding is a recognized source of error in wind turbine testing. Cup type anemometers usually speed up in increasing winds faster than they slow down in decreasing winds. It has been found, however, that as long as the distance constant is less than 5 meters the effect of anemometer overspeeding on the power output is not significant. The distance constant of the Maximum anemometer is 3 meters. Distance constant is defined as the length of constant wind following a step change for the anemometer to indicate 63% of the new wind speed.

5.3. ATMOSPHERIC EFFECTS

5.3.1 TEMPERATURE

The power output of a wind turbine is directly proportional to air density and thus to absolute air temperature. Figure 2 illustrates the effect of correction for air temperature on the Enertech power curve. There is a noticeable difference in the output power curves. The test was carried out during fall weather. Temperature effects during colder winter months could be even more pronounced. Figure 3 illustrates corrected and uncorrected power curves for 1989 obtained from test data on a 500 kW VAWT over a full year.

The effects of temperature on power variations within each bin however does not show such strong correlation. Figure 4 illustrates that the standard deviation of the power output with and without temperature corrections does not change appreciably.

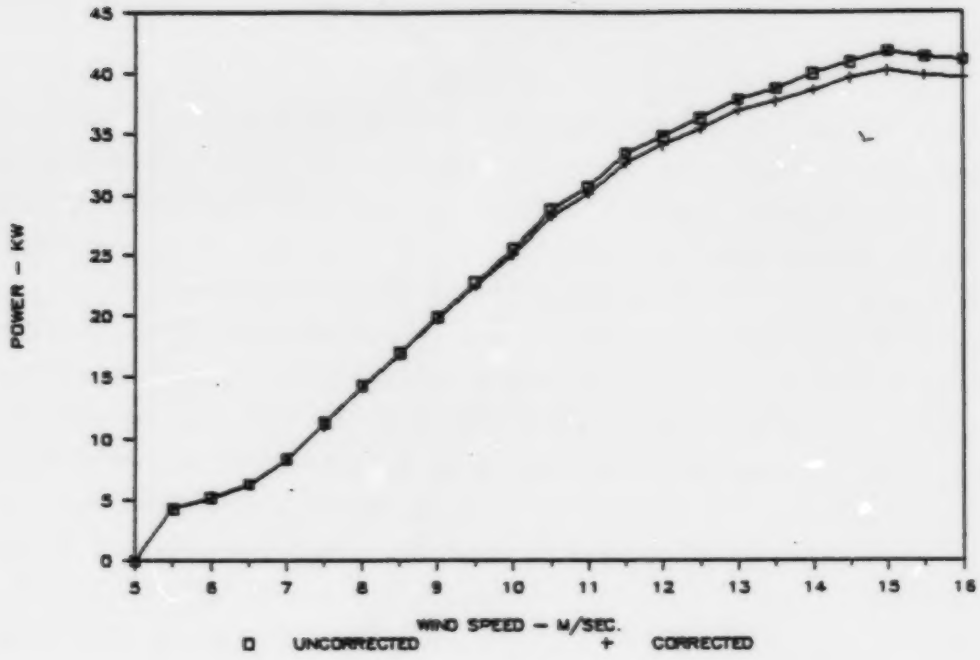

FIGURE 2 - ENERTECH POWER OUTPUT (TEMPERATURE CORRECTED AND UNCORRECTED)

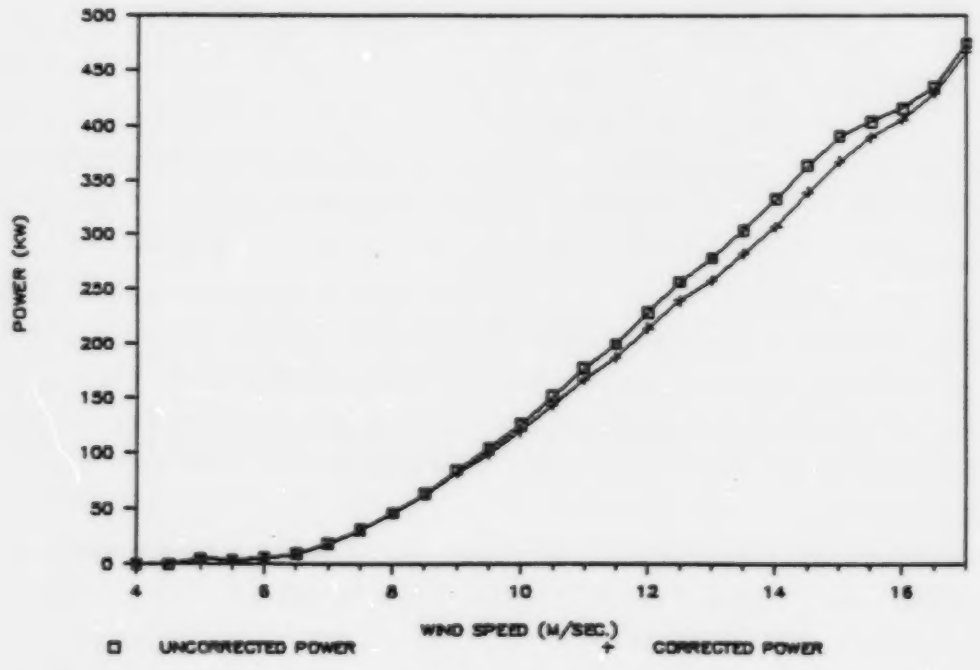

FIGURE 3 - AQUILO POWER OUTPUT (TEMPERATURE CORRECTED AND UNCORRECTED)

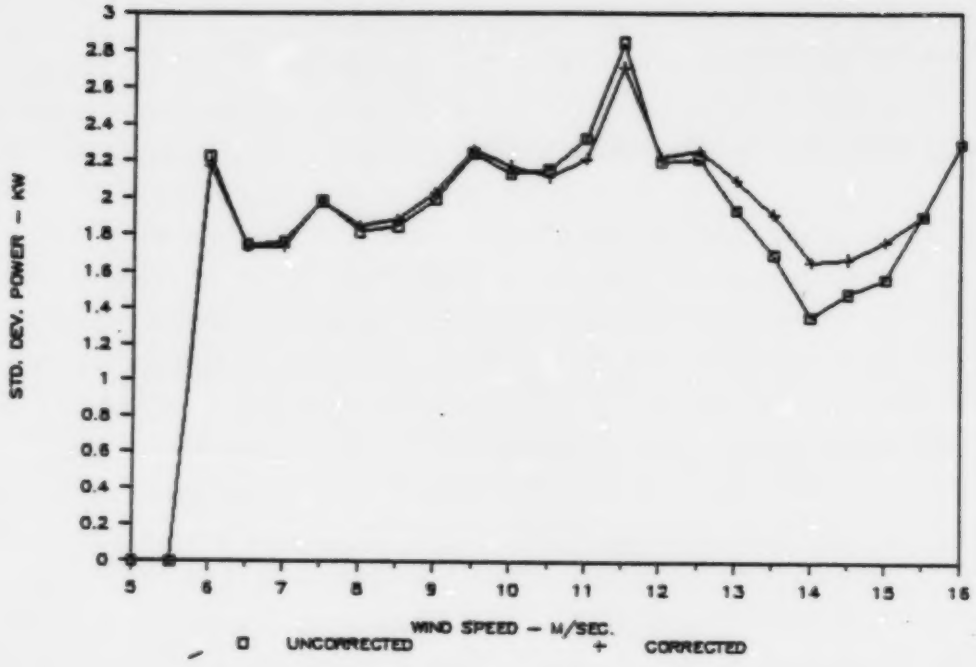

FIGURE 4 - ENERTECH STANDARD DEVIATION OF POWER (CORRECTED AND UNCORRECTED)

5.3.2. ICE/RAIN

There were no recorded incidents of icing during the test period but experience has shown that the effect of icing on performance is dramatic and that power levels decrease very rapidly with ice accumulation on the blades.

The effect of rain is less well understood. Experience at the national wind energy test station in West Germany suggest that rain has a detrimental effect on power output but there is insufficient

documentation to suggest magnitude.

5.4. TERRAIN EFFECTS

5.4.1. DIRECTION OF SELECTED WIND

The anemometer should be placed relative to the wind turbine such that the anemometer measures the same wind that the rotor sees. This is not actually possible since the anemometer samples a very small area compared to the rotor, is some distance from the rotor and not always directly up wind of the rotor. Nevertheless it is important that the anemometer measure as accurately as possible the wind that acts on the rotor. If the anemometer and wind turbine see the same wind the flow is said to be coherent. Wind that is sensed at the anemometer but does not flow through the wind turbine causes incoherence. Low frequency variations in wind speed are generally more coherent than high frequency variations because of the filtering effect of the wind turbine. The higher the incoherence between the wind flow that the anemometer and wind turbine see, the higher the probability of scatter and error in the power curve. To reduce this likelihood, limitations are placed on data acquired when the wind direction is such that there is likely to be incoherence between the anemometer and rotor. This would obviously exclude directions when the anemometer was downwind of the turbine. Other directions may also be excluded depending on terrain features, distance from the rotor and desired accuracy in the power curve.

During a wind turbine test the typical range of directions acceptable for data analysis is +/- 135 degrees on either side of a line down through the wind turbine and anemometer axis.

Figures 5, 6 and 7 illustrate that the standard deviation of the power output varies with the range of directional data that is included in the calculation. Power curves with wind from a 270 degree sector have a noticeably higher deviation than for a more

restrictive sector. This result is intuitively obvious. One would expect there to be more coherence as the sector dimension was reduced to allow only winds flowing directly past the anemometer to the rotor to be considered. The average standard deviation of anemometer #1 can be seen to drop from 2.0 at 270 degrees to 1.33 at 60 degrees. This restriction however also reduces the data available during any given test period.

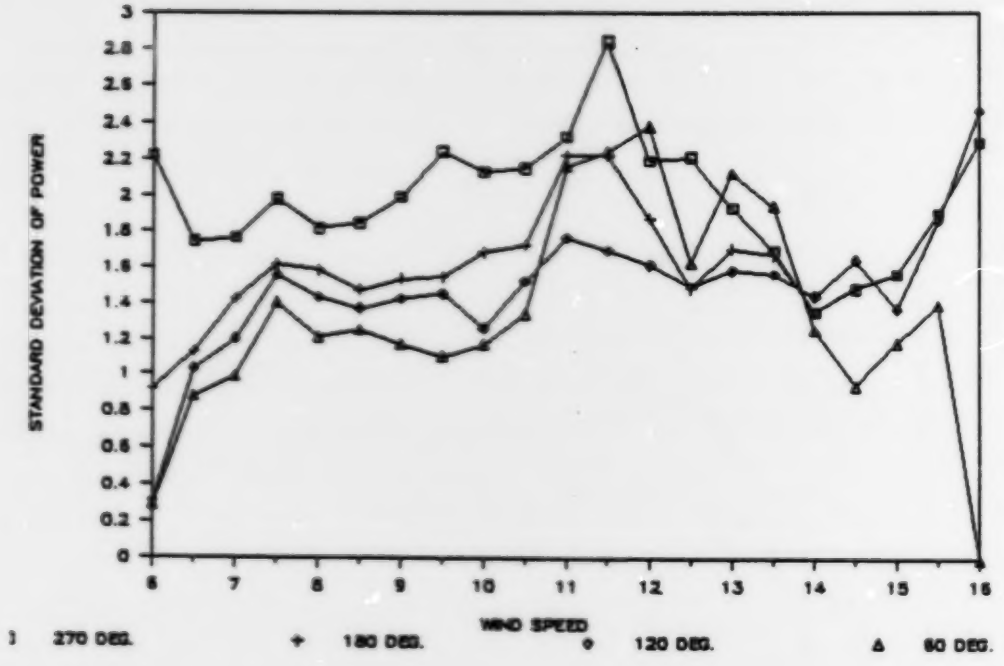

FIGURE 5 - DEVIATION OF POWER AS A FUNCTION OF ALLOWABLE WIND DIRECTION - ANEMOMETER #1

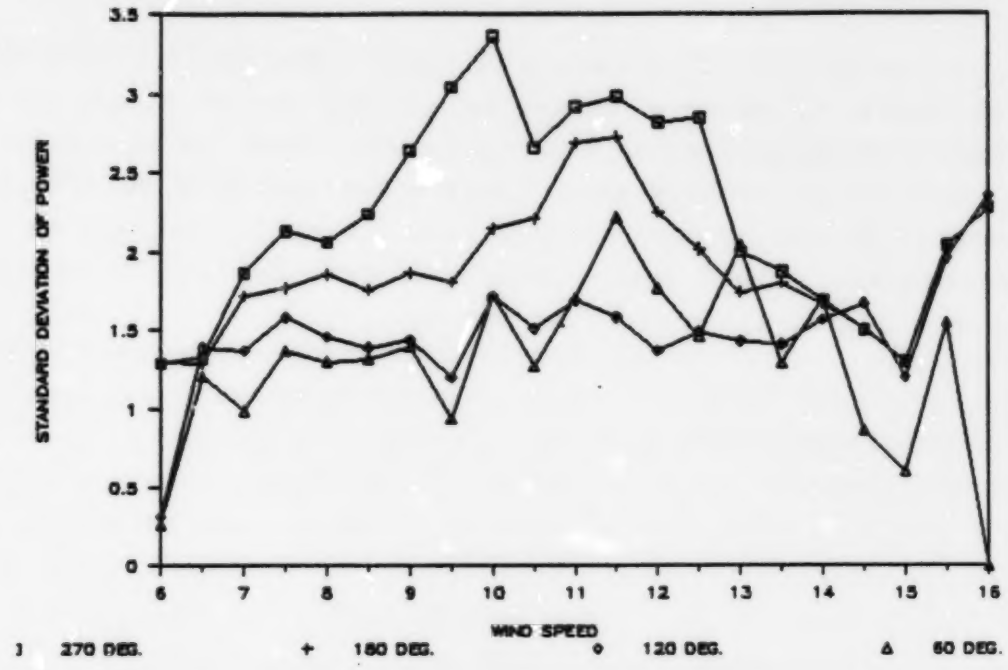

FIGURE 6 - DEVIATION OF POWER AS A FUNCTION OF ALLOWABLE WIND DIRECTION - ANEMOMETER #2

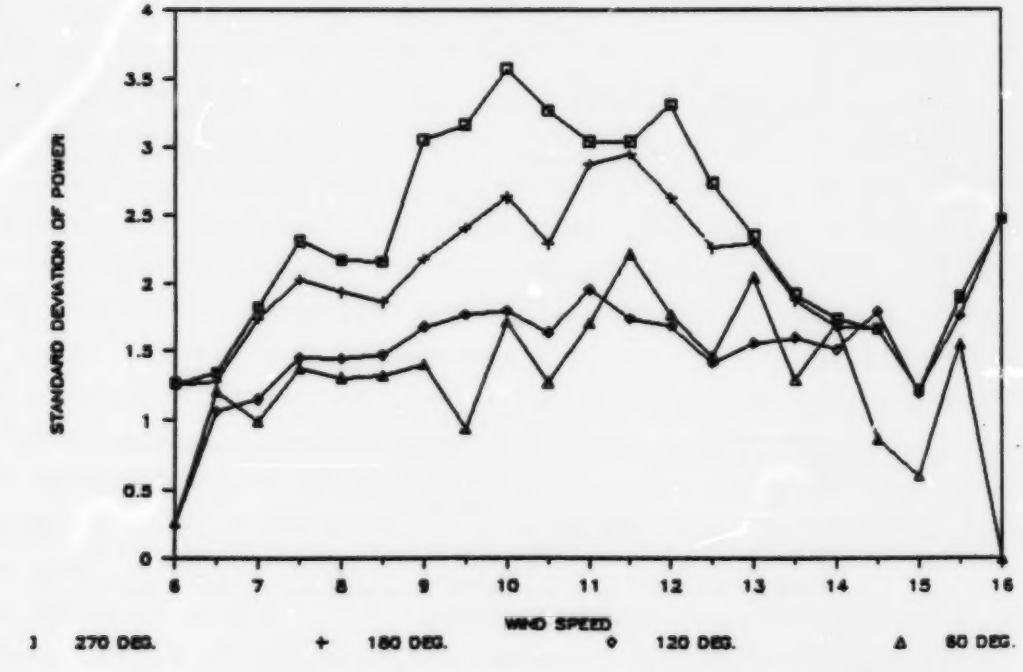

FIGURE 7 - DEVIATION OF POWER AS A FUNCTION OF ALLOWABLE WIND DIRECTION - ANEMOMETER #3

5.4.2. ANEMOMETER LOCATION

Reduced coherence can also be seen when anemometers are placed increasing distances from the wind turbine. Figures 8, 9, and 10 illustrate the increasing deviation as the anemometer distance increases and as the directional sector widens. At 270 and 180 degrees there is very pronounced increase in the deviation as anemometer distance is increased. At 120 degrees, however, there is a reduction in deviation levels.

The CSA standard and most other performance standards allow placement of the anemometer between 1.5 and 6 rotor diameters from the rotor. These locations were specified to permit some flexibility in locating anemometers.

Figure 8 illustrates the deterioration in coherence between anemometer #1 at 2 rotor diameters from the turbine and anemometer #3 at 5.8 rotor diameters causes an increase in deviation of about 25% for a 270 degree sector.

5.4.3. TURBULENCE

Turbulence is a measure of the variability of the wind and is often termed gustiness or level of gusting. Turbulence is usually considered to be a high frequency phenomena with variation of up to 1 Hz. Gusting takes place over space and time so that flow irregularities that are present between the anemometer and rotor are also present across the face of the relatively large rotor. These variations thus contribute to the deviation that is seen in the power output of the wind turbine. Figures 11 and 12 show variations over a one day period with relatively consistent winds from a generally constant direction. Figure 11 shows the wind speed, turbulence intensity and power output variation within the 8.5 m/sec. bin. The turbulence intensity, calculated as the ratio of standard deviation to average wind speed, varies from 4% to over

12% but generally lies in the 4-6% range. Over the period of this one day power output from the turbine varies from 14 to 22 kW. Similar variations are evident on Figure 12 for the 10.5 m/sec. bin on a different day.

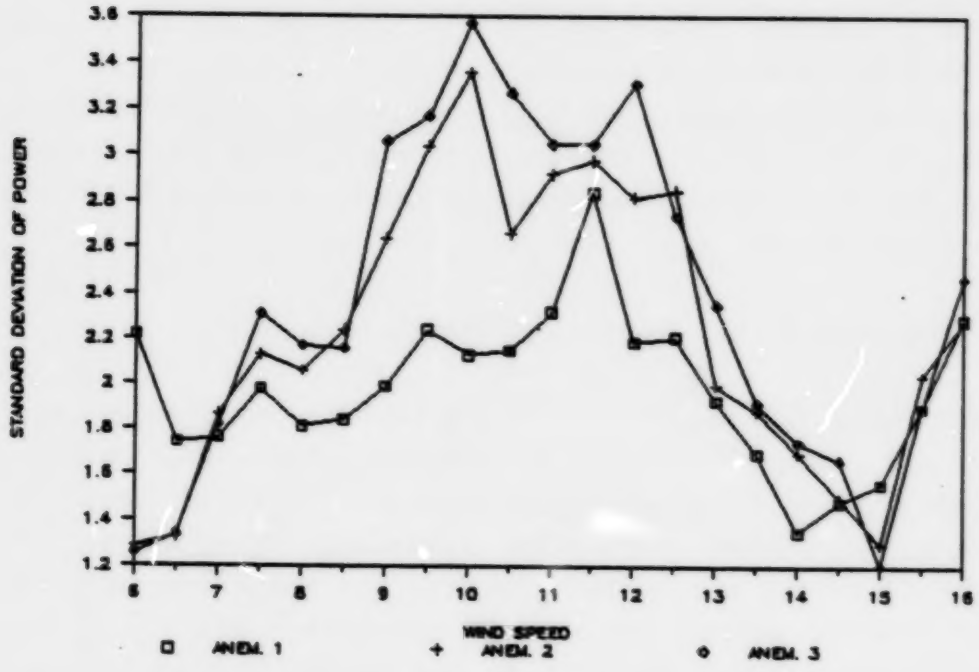

FIGURE 8 - DEVIATION OF POWER AS A FUNCTION OF ANEMOMETER PLACEMENT - 270 DEGREE RANGE

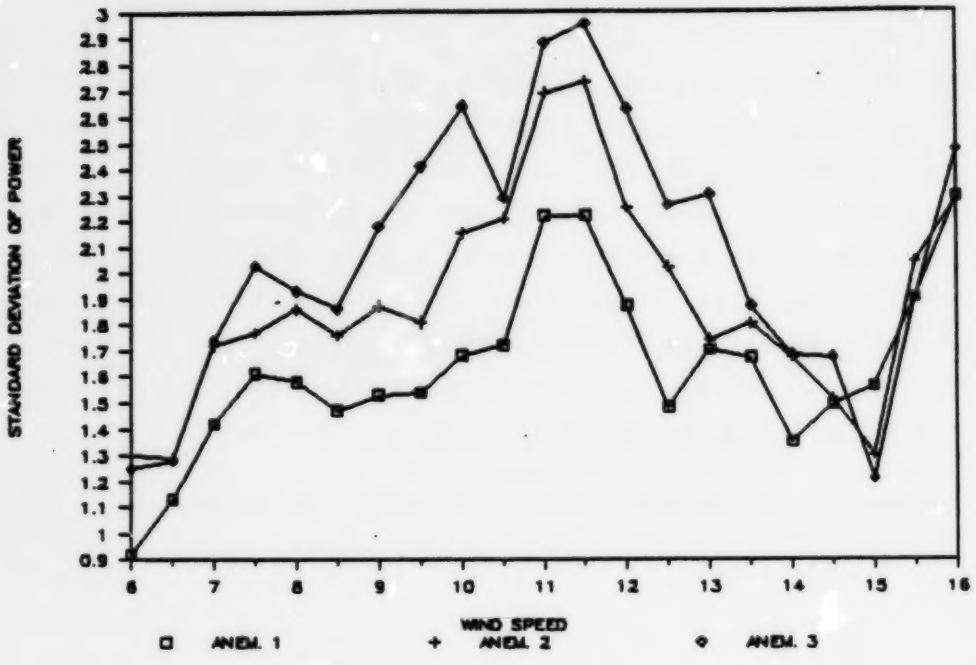

FIGURE 9 - DEVIATION OF POWER AS A FUNCTION OF ANEMOMETER PLACEMENT - 180 DEGREE RANGE

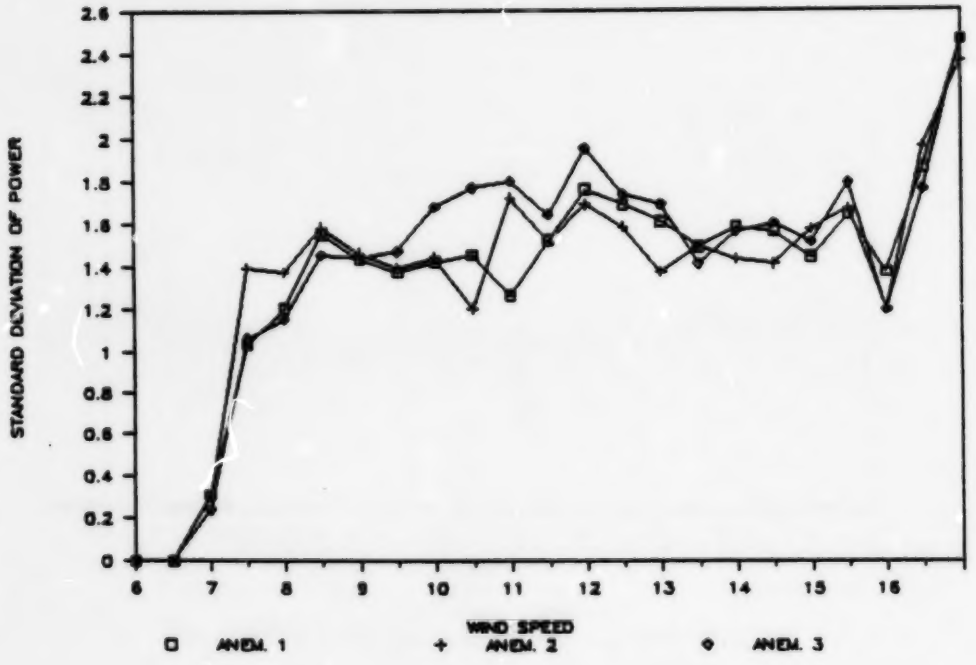

FIGURE 10 - DEVIATION OF POWER AS A FUNCTION OF ANEMOMETER PLACEMENT - 120 DEGREE RANGE

The turbulence level as shown on Figure 11 varies considerably over the day and one might consider this a factor in the wide variation in power output. There appears however to be no correlation between power output and turbulence when the entire dataset is examined. Figures 13 and 14 show the results of power output binned against turbulence for the entire test period. Average power levels do not appear to be related to turbulence intensity levels. This does not suggest that turbulence does not affect the power output, it simply means that average power output levels are not increased or decreased as turbulence intensity varies.

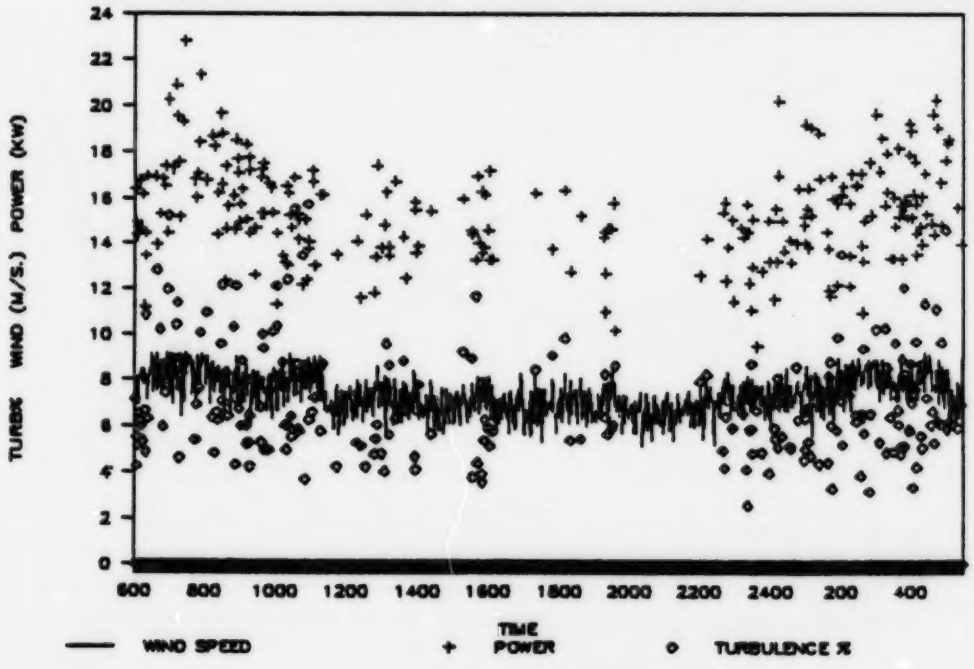

FIGURE 11 - TYPICAL DAILY VARIATION OF POWER WITHIN 0.5 M/SEC BIN

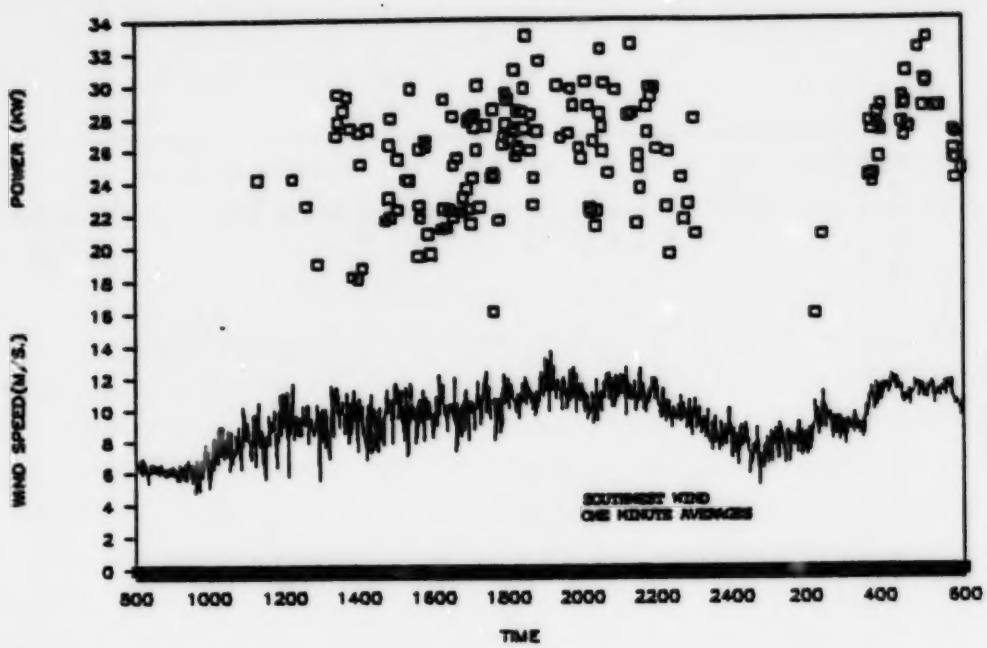

FIGURE 12 - DAILY POWER VARIATIONS WITHIN BIN 10.5 M/SEC (NOV.6/89)

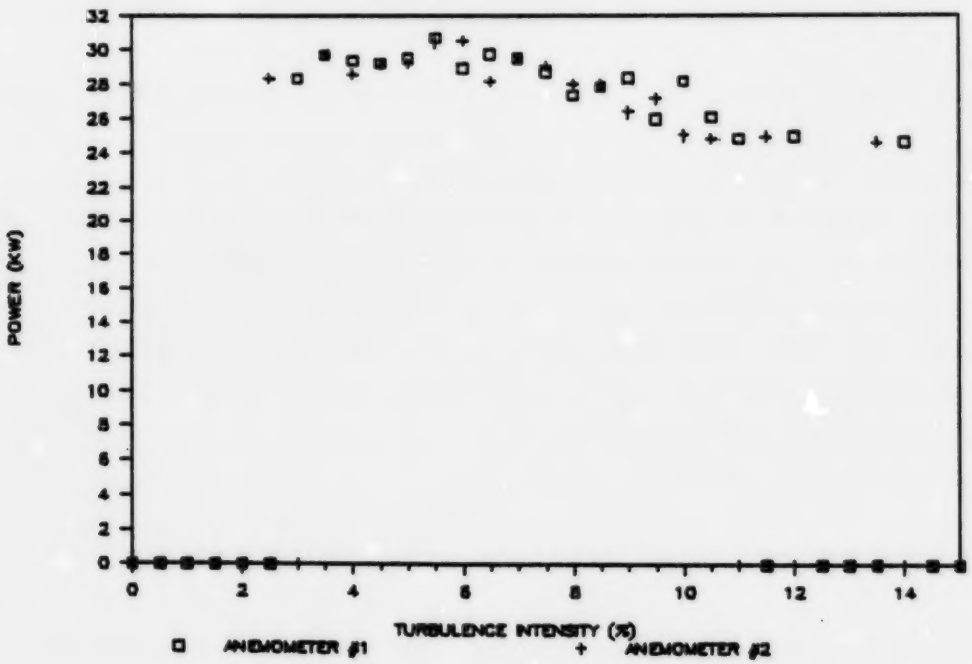

FIGURE 13 - EFFECT OF TURBULENCE ON POWER OUTPUT IN BIN 10.5 M/SEC

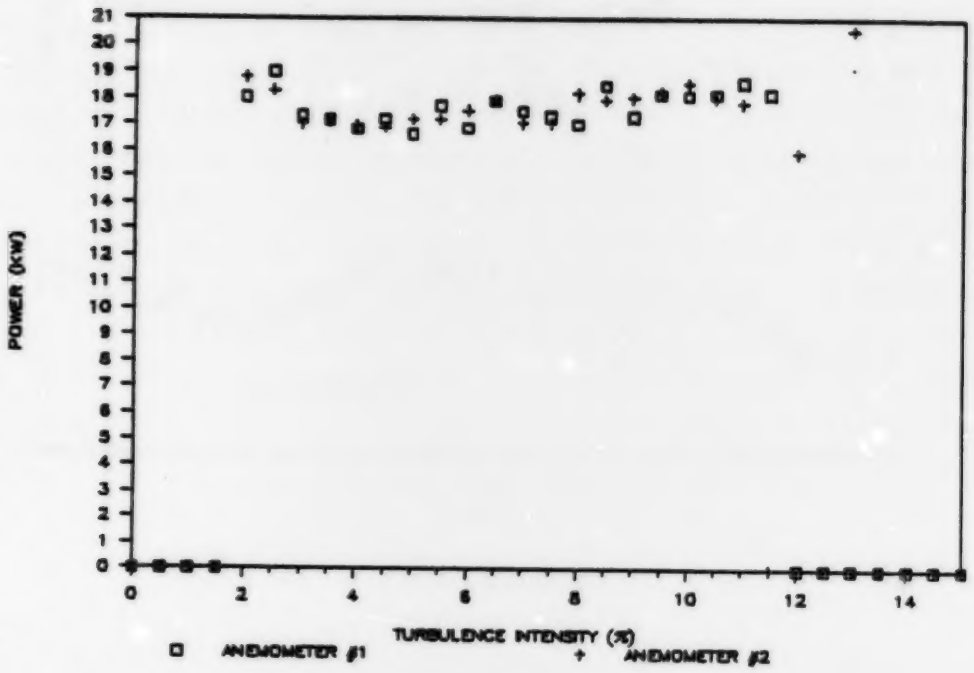

FIGURE 14 - EFFECT OF TURBULENCE ON POWER OUTPUT IN BIN 8.5 M/SEC

The above observations point to turbulence as the primary cause of deviation in the power curve. Turbulence across the rotor area and turbulence related coherence deterioration between the anemometer and the turbine appear to account for nearly all of the deviation in the power output.

5.5. STATISTICAL EFFECTS

5.5.1. EFFECTS OF POWER VARIATION WITHIN EACH BIN

The method of bins has become the accepted method of data analysis to determine the power curve of a wind turbine. As more fully described earlier the technique involves division of the wind speed range of interest into a number of equal intervals called

bins. The data averages for the parameters of interest, in this instance power, are accumulated into the corresponding wind bin as test data is acquired.

Since each bin is of finite width, there is a variation in power as the average values of binned wind speed values varies within the bin. Since the power available is a function of the cube of the wind speed, the increase of the wind speed within the bin will have some effect on the deviation of the power within the bin. For example; in the wind bin at 8.0 m/sec. (7.75 - 8.25) the power available increases by more than 20% from the lower to upper bounds of the bin. Actual output of a wind turbine will not increase by this much because of aerodynamic and mechanical efficiencies however power should increase somewhat across the bin thus some of the deviation seen may result from power variations within each bin.

Figure 15 shows the effects of power variation within the 8.5 m/sec. bin. There is, as expected, a substantial variation within the bin as the wind increases from the lower to upper range of the bin. However as Figure 16 shows these increases in power output do not reflect a similar variation in power deviation. The deviation of power at each sub-bin within the larger bin is very close (about 2.5 kW) to the same value as it is for the entire bin. This plot was taken from a large database using one minute averages and 270 degrees of wind direction. Other tests on smaller databases showed similar results.

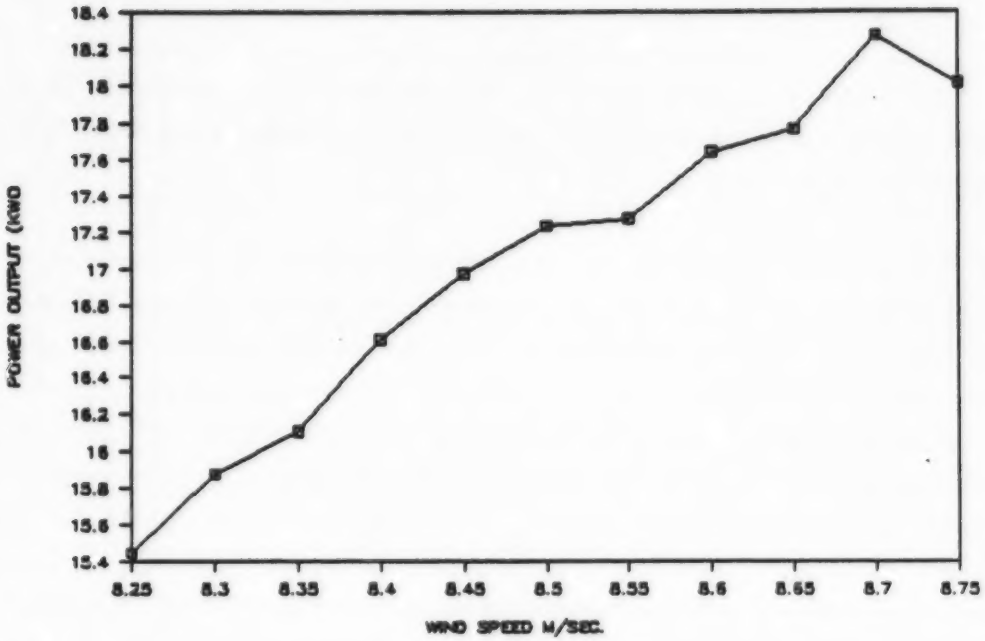

FIGURE 15 - EFFECTS OF BINNING WITHIN BIN 8.5 M/SEC

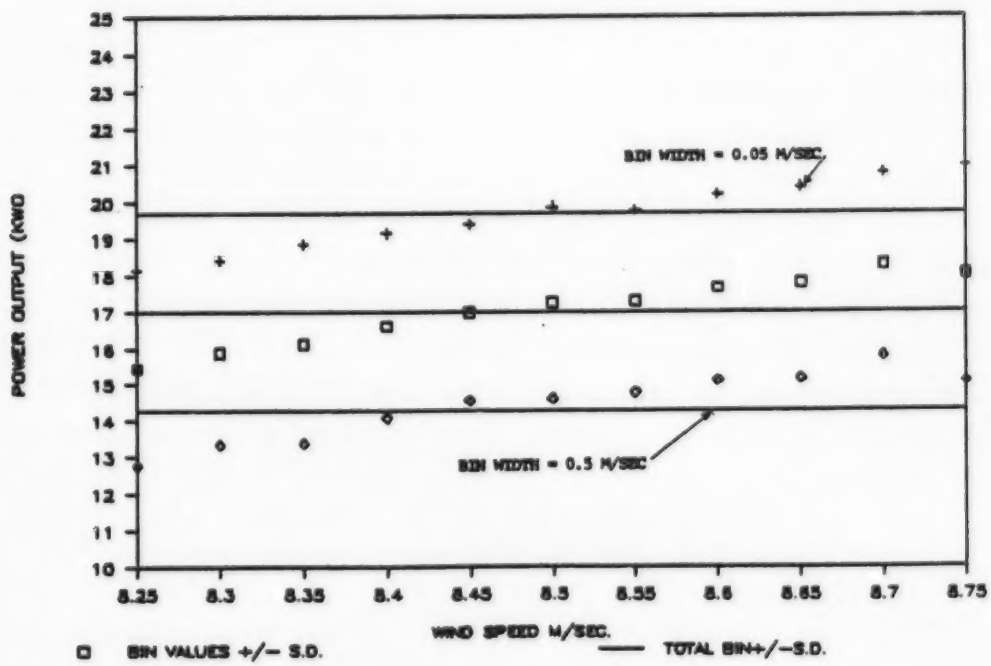

FIGURE 16 - AVERAGE POWER +/- STD. DEV. FOR BIN WIDTH OF 0.5 M/SEC AND 0.05 M/SEC

It is clear from this that the binning procedure does not account for the power deviations.

5.5.2. AVERAGING TIME

There are a wide variety of data acquisition and processing methods that can be used for testing wind turbines. However over time some methods have emerged as standard and preferred acquisition and analysis techniques in the CSA Standard.

Data collection is permitted by using chart recordings, simultaneous manual readings and similar methods. In fact, however, because of the difficulty in performing manual measurement essentially all wind turbine testing today is done using digital data acquisition systems in order to obtain the volume of data necessary. The sampling rate and averaging period capability of digital data acquisition system allows great flexibility during testing. In most testing programs, however, data is collected at a sampling rate of one hertz and is then averaged over ten minutes to provide the average value and standard deviation. Sampling rates may be at a higher rate or as low as 0.5 hertz provided the rate avoids specific frequencies where interaction with system natural frequencies may cause data problems such as aliasing.

Consideration has been given to the use of one minute averages to attempt to speed up the data acquisition process. Ten minute averages, however, have remained the most popular. Averaging times of less than one minute are generally not employed due to problems in correlating the wind speed and power outputs and complications caused by local turbulence. Both ten minute or one minute averaging intervals have advantages and disadvantages. The shorter averaging times provide a wider velocity range and require a shorter period to accumulate a database. The longer averaging time provides for a reduced statistical error and better correlation between the anemometer and wind turbine.

Figure 17 illustrates the power curves obtained for the one minute and ten minute averages for a directional sector of 270

degrees. They can be seen to be identical, suggesting that either one minute or ten minute averages are acceptable. A similar comparison of all anemometers and all direction sectors provided similar results for one and ten minute averages. Figure 18 illustrates the average and standard deviation for both averaging times. One minute values are indicated by symbols and ten minute values by lines. The results, as expected, indicate that the one minute averages have a slightly higher level of deviation than the ten minute averages. The only significant difference is that at the lowest power levels the ten minute averages converge to zero power at 5.5 m/sec, while the one minute averages show some power levels as low as 5 m/sec.

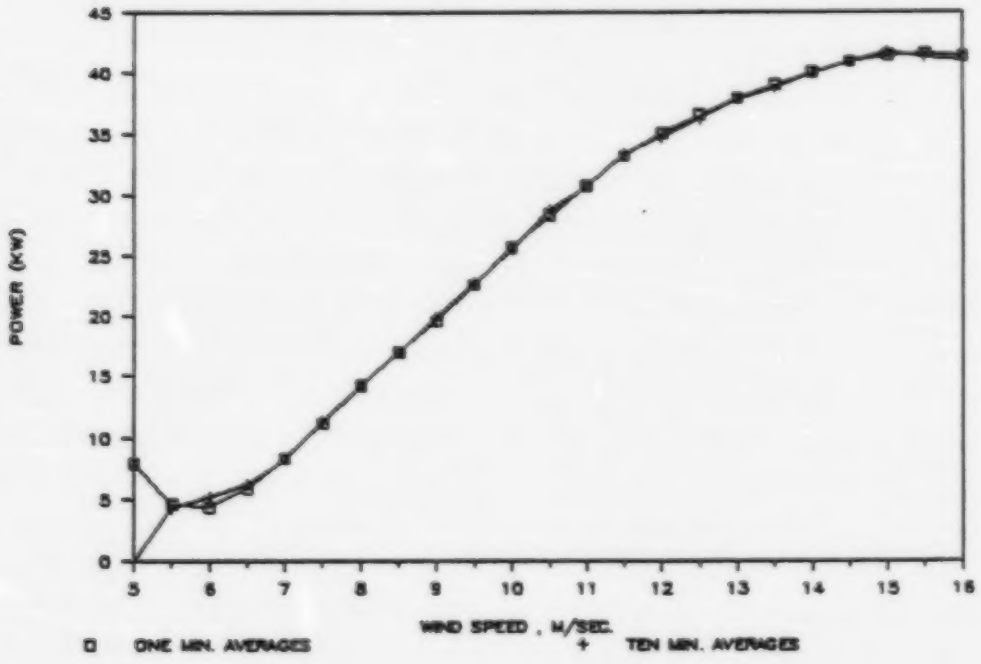

FIGURE 17 - COMPARISON OF POWER CURVE USING ONE AND TEN MINUTE AVERAGES

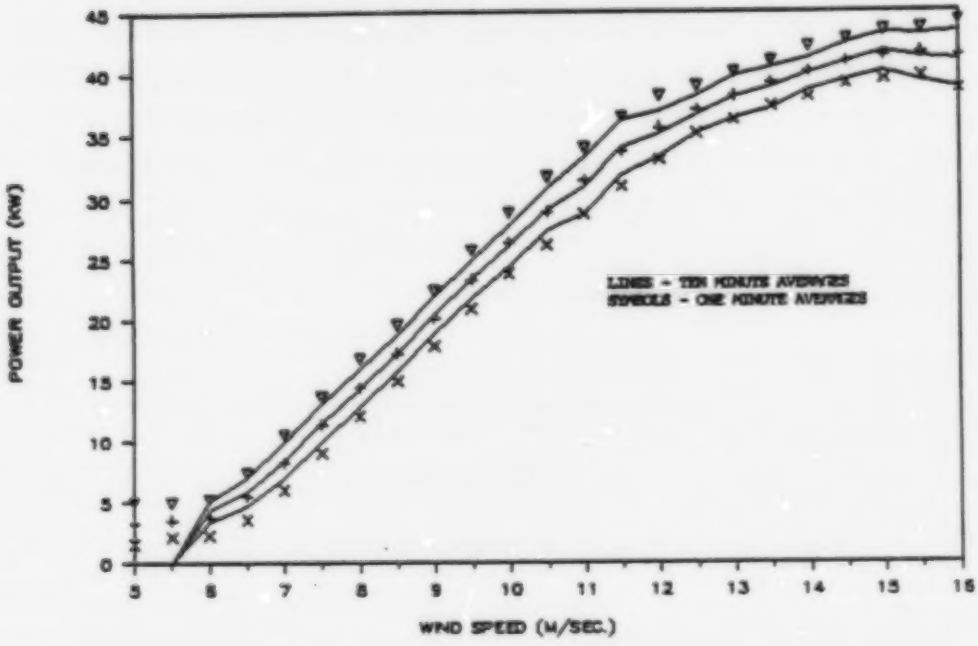

FIGURE 18 - COMPARISON OF STANDARD DEVIATION OF POWER USING ONE AND TEN MINUTE AVERAGES

5.5.3. POWER DISTRIBUTION WITHIN BIN

A statistical analysis of data within a bin introduces some interesting information.

Since the distribution of the wind over a long period of time approaches a Weibull distribution, the long term distribution of the wind within a small range of wind speed in a typical small bin will be more or less linear with a slight slope depending on what segment of the Weibull curve it represents. Figures 19 and 20 which are plots of the wind speed distribution within the 8.5 and 10.5 bin illustrates that binning the wind speed within each bin results in a nearly linear distribution across the bin.

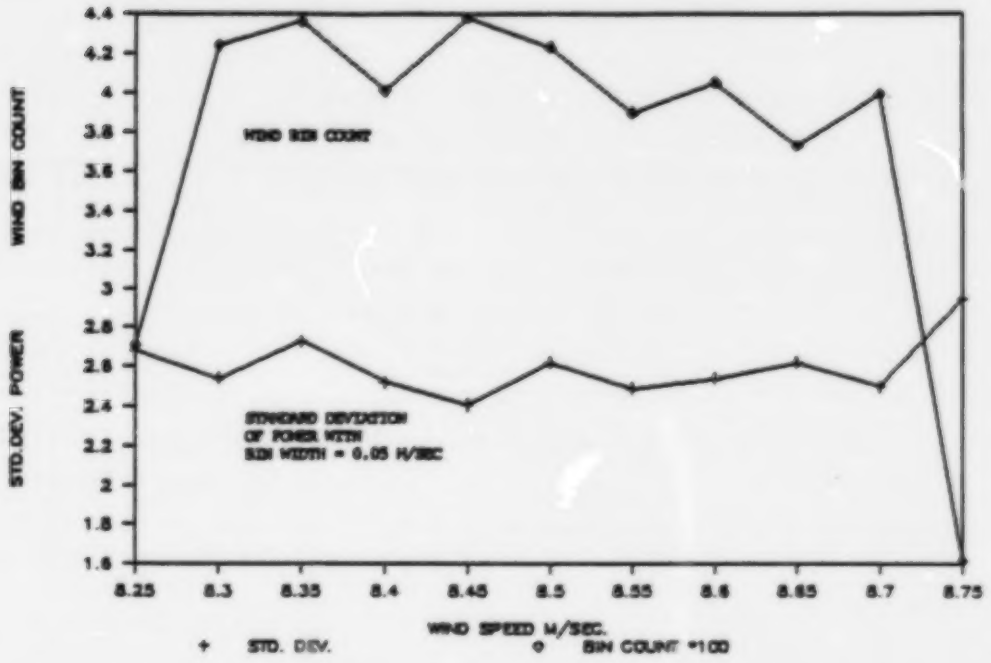

FIGURE 19 - DISTRIBUTION OF WIND AND STANDARD DEVIATION WITH BIN WIDTH = 0.05 M/SEC

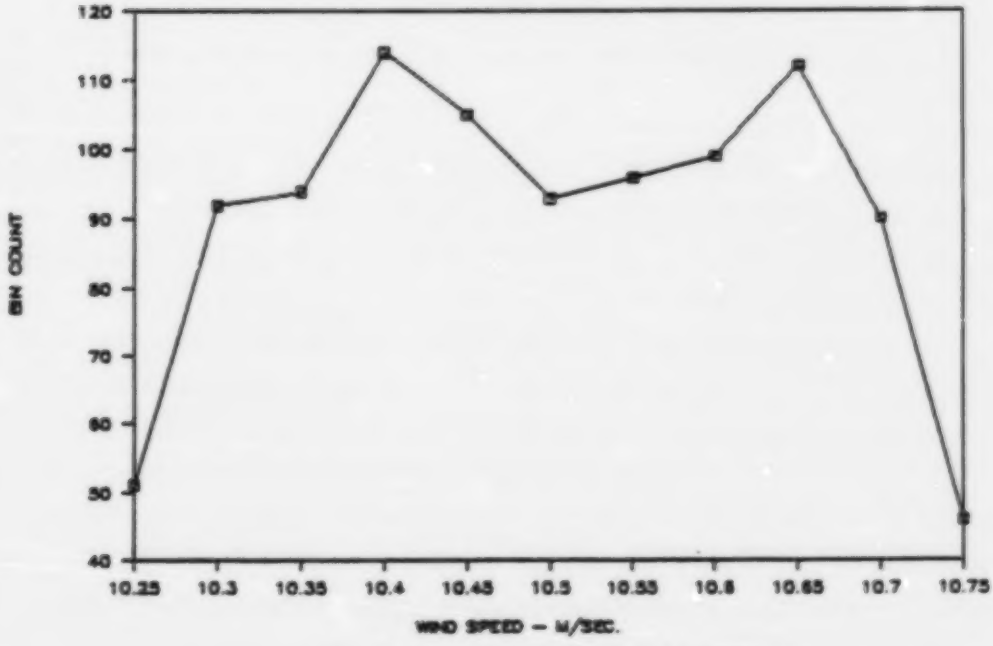

FIGURE 20 - BINNED WINDSPEED WITHIN 10.5 M/SEC BIN

If the power output of the wind turbine were a simple linear function of the wind speed one would expect a similar distribution of power. However the distribution of the power within the bin is a function of more complicated random variables and does not follow the same distribution. In fact the accumulation of random variable effects results in a power distribution that eventually forms a normal distribution within the bin. Figures 21 and 22 are plots of the power distribution corresponding to Figures 19 and 20 and illustrate this quite clearly. Similar evaluations on other bins provide the same results.

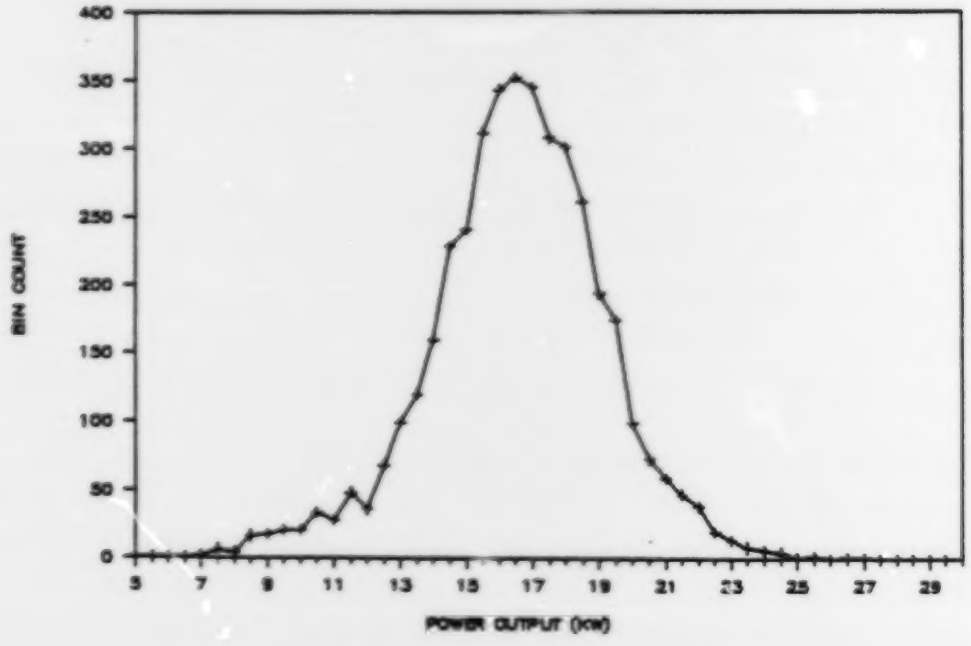

FIGURE 21 - POWER DISTRIBUTION WITHIN 8.5 M/SEC BIN

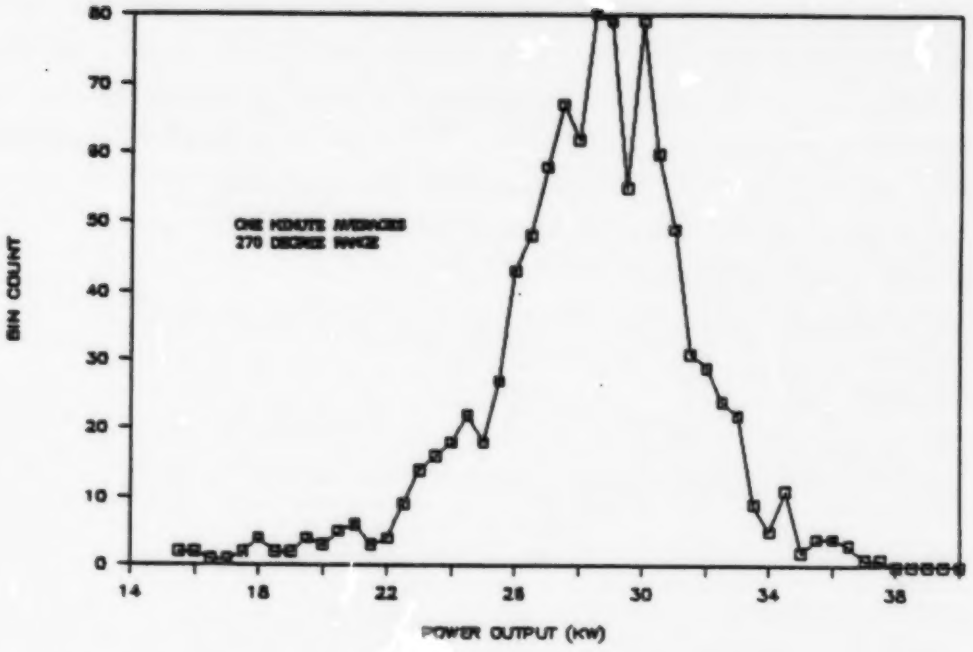

FIGURE 22 - POWER DISTRIBUTION WITHIN 10.5 M/SEC BIN

An important consequence of this result is that if the distribution of the power within a bin is normally distributed, then routine statistical analysis should be applicable. This would suggest that the original method of analysis proposed by the CSA performance standards committee should work. This runs counter to the conclusions of the first three field test results carried out after the completion of the draft standard and thus an investigation of this apparent contradiction is in order.

5.5.4. THE 'T' STATISTIC

The appropriate test to estimate the mean of a normal population with unknown variance using a small number of samples is the 'T' statistic.

The method was proposed in the original CSA standard and is briefly described here.

The important variables in measuring performance of wind turbines is the average and standard deviation of the wind turbine power output in each of the wind speed bins. The average or mean is simply the sum of the bin entries divided by the number of entries. Standard deviation is an indication of the amount of variation within the various bin entries. The smaller the standard deviation the more closely the bin entries are packed around the mean. If an infinite number of samples were taken the mean and standard deviation of the bin entries could be accurately calculated as they would have more or less asymptotically converged as the number of samples increased to the final value. The purpose of this technique is to reduce the amount of data required to a relatively small number of samples that will still provide averages and standard deviations with reasonable statistical accuracy.

The analysis is carried out by calculating a cumulative average value and standard deviation for each wind speed bin. The cumulative average value is adjusted slightly with each additional sample using the appropriate 'T' test constant to calculate an acceptable standard deviation that would meet the test criteria. When the standard deviation decreases to a value less than the calculated value the criteria is met.

The minimum acceptable standard deviation σ_{min} is calculated as:

$$\sigma_{min} = \frac{A \cdot P \cdot N}{'T'}$$

where:

A = maximum error from the mean (In CSA F417 it was proposed to use 0.05 (5%) for wind speed less than 15 m/sec. and 0.10 (10%) for wind speeds greater than 15 m/sec.)
P = cumulative average power in the bin
N = number of samples in the wind speed bin
'T' = test constant based on the confidence level desired for the analysis and dependent on the number of samples in the wind speed bin.

The 'T' constant increases for decreased confidence levels and decreases asymptotically as the number of samples increase.

Figure 23 illustrates the allowable standard deviation and number of samples for two confidence levels and levels of acceptable errors at 17 kW. As the confidence level and the accuracy of the estimate increases the required standard deviation decreases. It can be seen that if the test period is to be very short the standard deviation of the test values must be very small. As the number of samples increases the allowable deviation also increases.

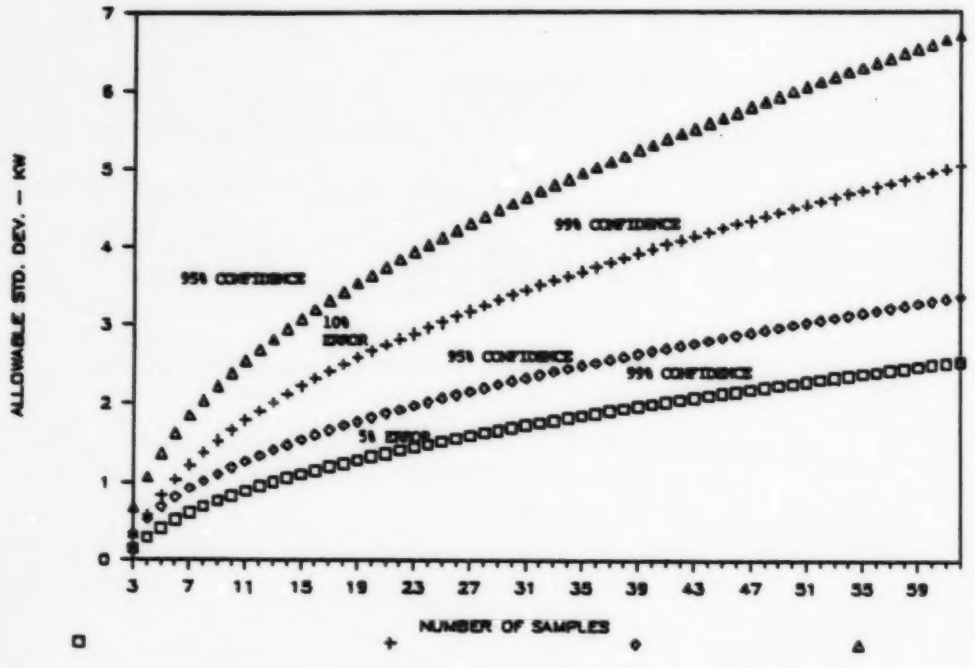

FIGURE 23 - 'T' TEST - ALLOWABLE STANDARD DEVIATION TO CONFORM TO LEVELS OF CONFIDENCE/ERROR AT 17 KW POWER OUTPUT

5.5.5. ANALYSIS OF ENERTECH DATA USING CSA F417

Since the distribution of the data obtained appeared to be suitable for the statistical analysis proposed in CSA F417, a study was carried out to determine if the test criteria could be met. Figures 24 and 25 illustrate the cumulative analysis conducted on the one minute data in the 8.5 and 10.5 m/sec. bins. The criteria is met to within 5% error after only about 20 samples in either bin. Less than 10 samples are required to define the mean within

10%. Figures 26 and 27 illustrate the results of a similar analysis carried out on ten minute averages for the same bins. Similar amounts of data were found to be required to meet the same criteria as the one minute averages. The deviation of the one minute averages as noted earlier is higher than for the ten minute averages but the higher level does not impair the ability to use one minute values in meeting the criteria of the standard.

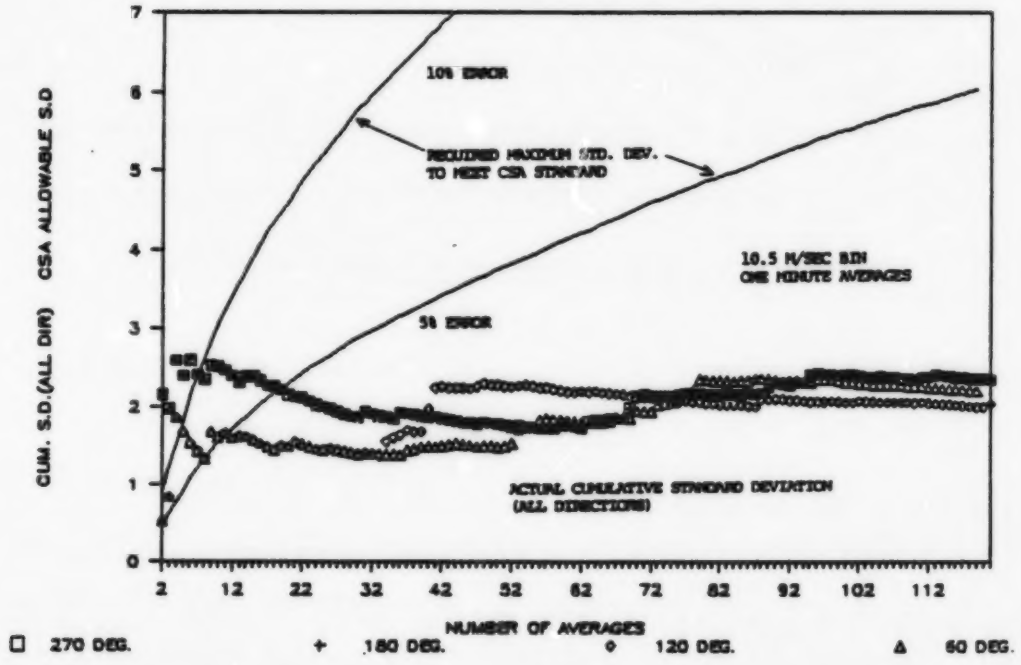

FIGURE 26 - ACTUAL DATA REQUIRED TO MEET CSA STANDARD (10.5 M/SEC, 1 MIN AVG)

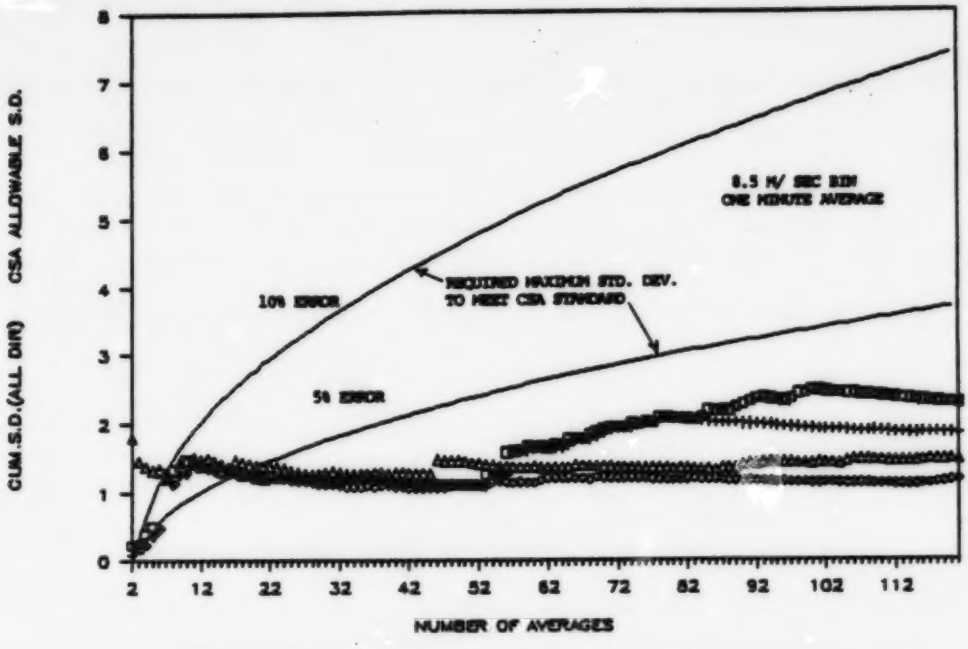

FIGURE 25 - ACTUAL DATA REQUIRED TO MEET CSA STANDARD (8.5 M/SEC, 1 MIN. AVG.)

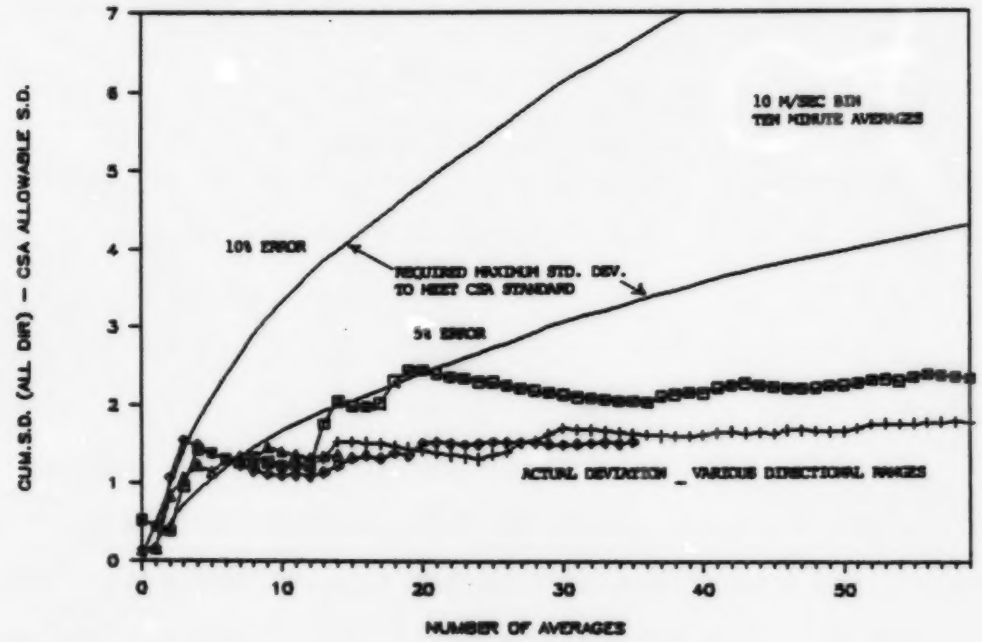

FIGURE 26 - ACTUAL DATA REQUIRED TO MEET CSA STANDARD (10.5 M/SEC, 10 MIN. AVG.)

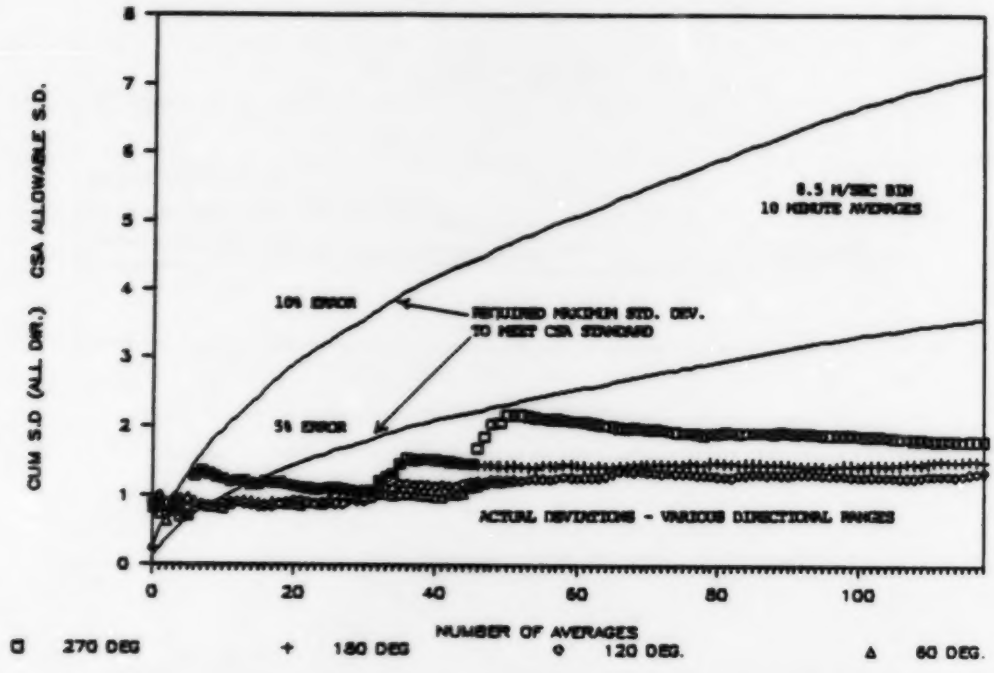

FIGURE 27 - ACTUAL DATA REQUIRED TO MEET CSA STANDARD (8.5 M/SEC, 10 MIN AVG)

5.5. REVIEW OF THE ORIGINAL TEST DATA

It is interesting to consider why this machine conforms so well to the CSA F417 when the three test machines used previously to carry out the field test all failed to meet the criteria. A detailed review of the original data is not possible since data formats have changed at AWTS. However a review of the original test data shows why the units failed to meet the necessary

criteria. The standard deviations in all cases were simply too high to conform to the standard. The standard deviation expressed as a percent of power output for the Enertech is substantially less than 10%. For the units tested in the original field test the value was somewhat higher. This was evident in the upper and lower power ranges for both the grid connected unit and the battery charging unit and over the entire power range for the water pumper. The reasons for the high deviation in the original test units compared to the Enertech was probably due to a number of reasons. The Enertech tower is much higher (25 m) than the early test units and therefore subjected to less turbulent flow. By comparison the grid connected machine used in the previous test was a vertical axis machine with an equator height of only 7.5 meters from the ground.

The test was also conducted over shorter period of time at a different time of the year. This test was conducted during the windy fall months. The previous test was carried out in the spring when wind speeds were generally lower and provided more data in the lower wind speed bins where the hysteresis near cut-in affected the deviation. In the upper wind speed bins there was not sufficient data to meet the CSA criteria.

The variable speed operation of the battery charging unit affected the deviation at the more frequently occurring lower wind speeds.

For the water pumper the variable speed operation coupled with the high hysteresis at startup and poorly matched pump/rotor

characteristics also contributed to the high deviation.

5.7. CSA TESTS USING 500 KW VAWT 'AQUILO'

Since the analysis of the Enertech shows validity to the CSA E417 proposed method of determining minimum data base requirements a similar analysis was carried out on power performance data obtained in 1989 from the Indal 500 kw vertical axis wind turbine at AWTS.

Before initiating analysis the data in several bins was examined to confirm that it was properly distributed. Figure 28 shows that power within the 10.5 m/sec. bin 10.5 is distributed in an approximately normal manner.

Two anemometers were used on this machine, one located 4 rotor diameters to the north and one located 3.5 rotor diameters to the northwest, in the direction of the prevailing winds.

Figure 29 plots the cumulative average power in the 10.5 m/sec. bin over a directional sector of 270 degrees. After 200 samples the average values coverage to a common mean at about 143 kW. After only the first few samples however, there is a wide discrepancy in the means. This is probably due to terrain effects at AWTS. Figures 30 and 31 plot the CSA MCBR test against the standard deviation of the power output. In both instances over 60 samples are required to achieve 5% error and about 20 points to determine the mean value of the bin within 10%.

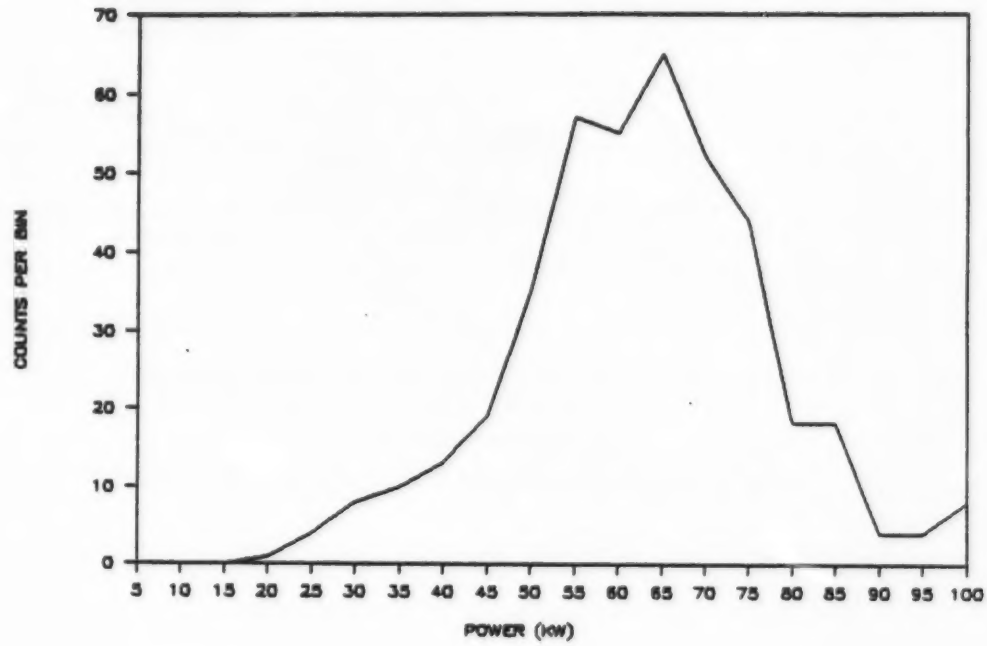

FIGURE 28 - AQUILO - DISTRIBUTION OF POWER WITHIN BIN 8.5 M/SEC

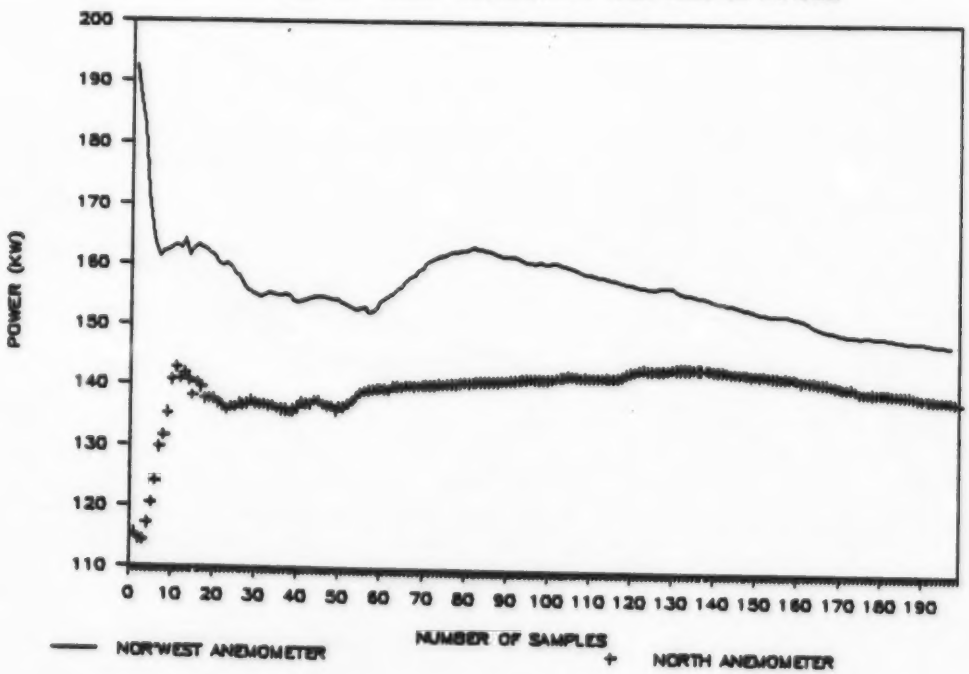

FIGURE 29 - AQUILO - CUMULATIVE AVERAGE POWER IN BIN 10.5M/SEC - 270 DEGREES RANGE

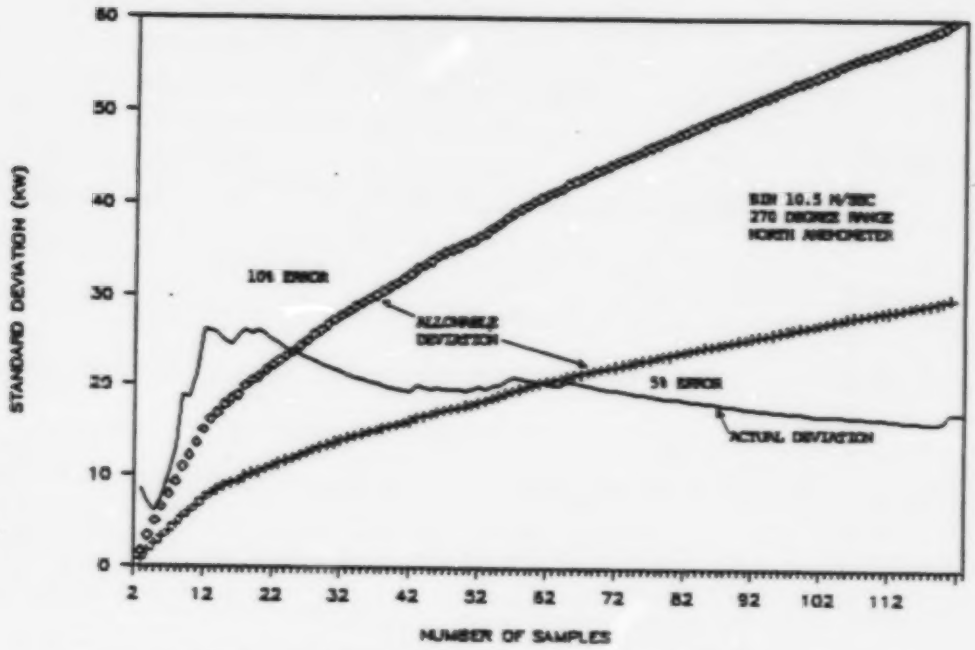

FIGURE 30 - ACTUAL DATA NECESSARY TO MEET CSA STANDARD (NORTH ANEMOMETER(270 DEG.)

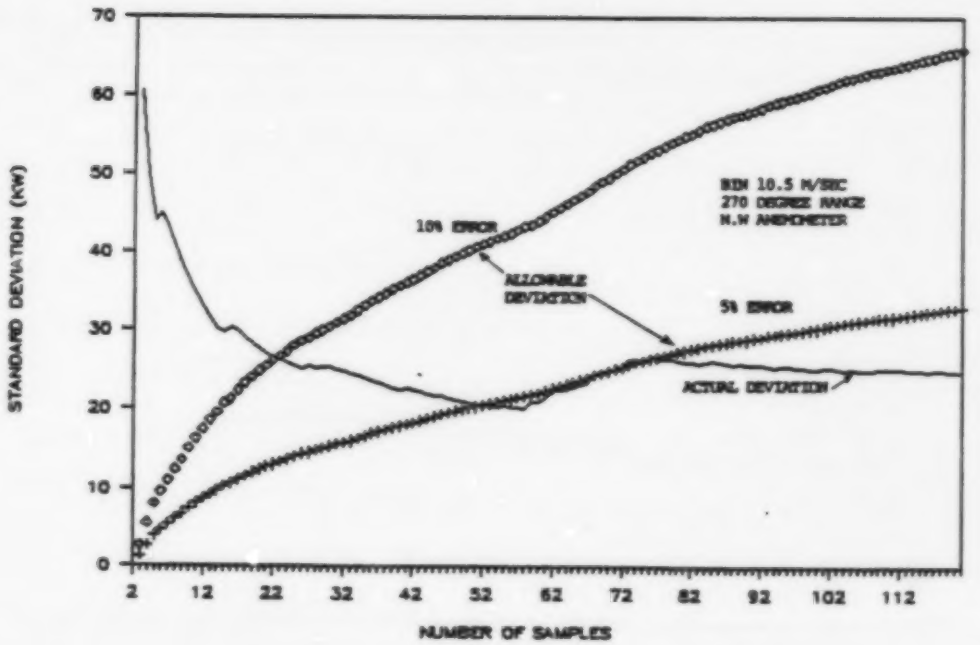

FIGURE 31 - ACTUAL DATA NECESSARY TO MEET CSA STANDARD (N.W. ANEMOMETER(270 DEG.)

In an attempt to reduce the data required to predict the power curve the permissable direction sector was reduced to 120 degrees. Figure 32 illustrates that this serves to stabilize the cumulative average very quickly, especially for the north anemometer. The northwest anemometer still takes several values before it stabilizes and again this is probably due to local terrain effects. Figures 33 and 34 illustrate the effect that reducing the acceptable directional angle makes on meeting the criteria of the CSA test. The north anemometer meets the necessary 5% error criteria after about 10 samples and the northwest anemometer does not meet the criteria for nearly 30 samples. The significance of this is that with similar limitations on the allowable direction and anemometers placed at identical distances from the rotor, there were significant variations in time and number of samples needed to meet the criteria. This underscores the necessity of careful planning and a fundamental understanding of wind flow pattern before any test is initiated. It also points out some shortcomings in stating the need for a given confidence level to be achieved before a performance test is concluded. Under certain conditions it may be virtually impossible to meet the criteria in a reasonable length of time.

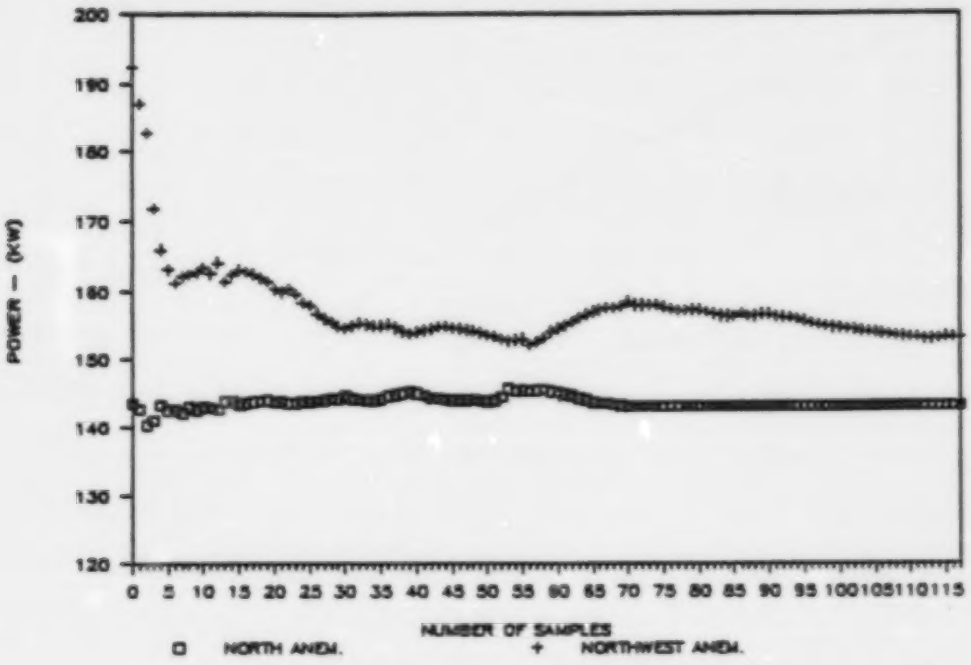

FIGURE 32 - CUMULATIVE AVERAGE POWER IN BIN 10.5 M/SEC - 120 DEGREE RANGE

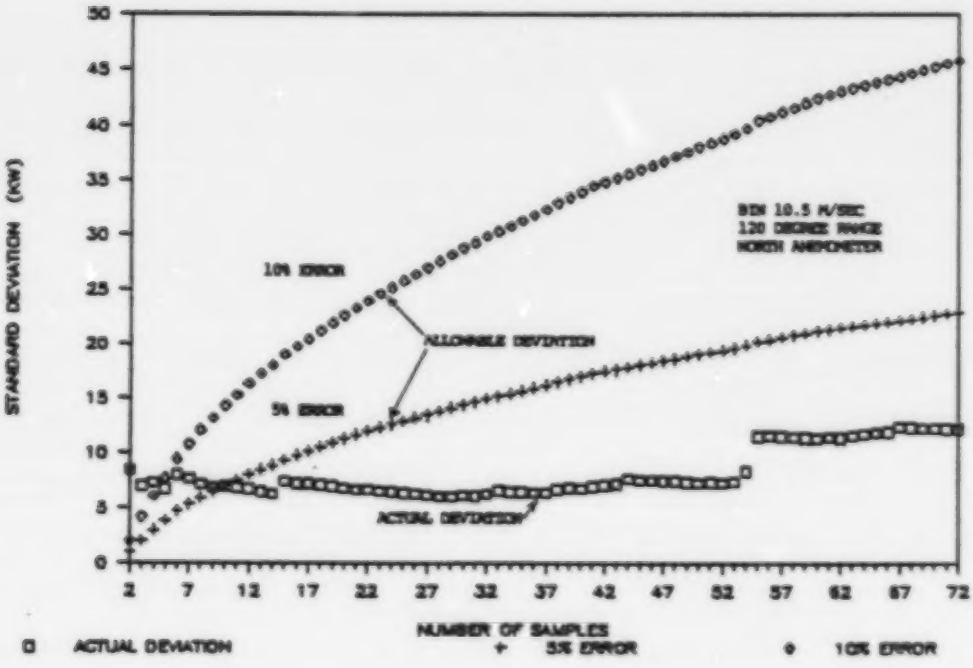

FIGURE 33 - ACTUAL DATA NECESSARY TO MEET CSA STANDARD (NORTH ANEMOMETER)(120 DEG)

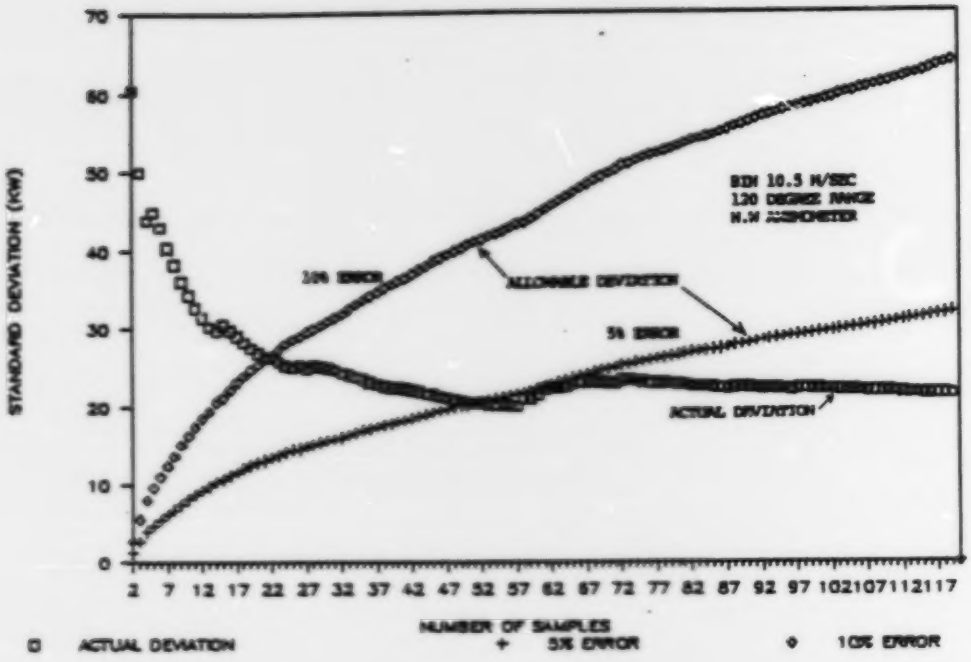

FIGURE 34 - ACTUAL DATA NECESSARY TO MEET CSA STANDARD (R.M. ANEMOMETER-120 DEG.)

8. CONCLUSIONS

A number of conclusions can be made as a result of this study. Some are directly relevant to the CSA standard and some are just interesting observations.

In this test a number of factors were investigated to determine whether they were a significant source of deviation in power output within each bin. The effect of each factor is described below.

Machine effects were observed to be negligible. No discernible degradation in performance was observed due to dirty blades, yawing error or any other aerodynamic, electrical, or mechanical problem.

Temperature, as expected is directly related to power output. Comparison of corrected and uncorrected power output curves show substantial variations due to temperature. This would suggest that temperature correction is necessary to standardize wind turbine power curves. In colder climates a bonus in the form of additional output may be available if testing to produce the power curve was performed at a warmer location.

Instrumentation effects should be negligible. However the insidious nature of intermittent sensor problems and the ubiquitous presence of 'Murphy' requires constant attention throughout a test program.

Terrain related effects are a major factor in the deviation of power measurements. Turbulence across the rotor disc and turbulence induced incoherence between the rotor and anemometer account for the majority of the deviation present in the binned data. The deviation can be reduced by judicious selection of directional sectors and anemometer placement. The effect of varying these parameters is site specific. Anemometer placement should be as close to the rotor as possible without being influenced by the upwind effect (blockage) of the rotor. Selecting a directional sector is necessary to ensure reasonable deviation of the data. The optimum sector is one that allows the mean of a bin to be calculated with an acceptable error within a given period of time. The variables that must be optimized in each instance are the deviation permitted and the time available for the testing. Clearly selecting the direction within only several degrees may provide great accuracy however the time required to accumulate a database would be unacceptable. Test results in this instance suggest that an angle of exclusion of 270 degrees for the anemometer located at two rotor diameters from the tower would be optimum.

Statistical effects play a minimal role in reducing the deviation within a given bin. Bin width does not appear to affect deviation however power levels do vary from minimum to maximum values within the bin. Using an averaging time of ten minutes will reduce deviation slightly but at a substantial increase in time. One minute averaging periods provice averages identical to those

obtained from ten minute periods. They also provide a larger database and improved resolution, at a very slight increase in deviation. Consideration should to be given to their use when time is an important factor.

7. RECOMMENDATIONS

After consideration of the data analysis results and a review of the CSA standard F417 the following modifications are recommended to the section of CSA F417 cited.

5.4.2.1 LOCATION

It is recommended that this section be appended to recommend that the anemometer be located within 2 rotor diameters from the centre of the rotor in a direction where topographical effects will be minimized and prevailing winds will be accurately monitored.

6.3.1 DATA GATHERING

It is recommended that data gathering be limited to digital data acquisition equipment properly calibrated and programmed to carry out the function at an appropriate data sampling rate. Given the decreased cost of digital data loggers in recent years and the

obvious problems inherent with alternate data collection techniques the increased accuracy of using this type of equipment relative to its modest cost make it an essential tool in wind turbine testing.

6.3.2 SAMPLING RATE

The recommended sampling rate should be one hertz or faster.

6.4.2.1

Recommendations from the original field test recommenced using Chauvenet's criteria to assist in the elimination of bad data. This recommendation is repeated here.

6.4.2.2

It is recommended that the following be appended to this clause: In some instances, due to topographical effects, it may be desirable to be more restrictive on the direction used for data exclusion.

6.5 ANALYSIS OF FIELD RESULTS

6.5.1

It is recommended that the option be given to using one minute averages if so desired. Test results in this instance snow that accuracy is not lost and testing can be completed more rapidly. If there is ample time to conduct the test ten minute averages require substantially less data processing. Whichever method is used should be stated clearly.

6.5.2

As the above comments indicate the present format for minimum data base requirements should be adequate for most test programs with enough time and with no unusual problems. However as the original test program has indicated there are instances when the test criteria is simply not met. This will occur more frequently with poor or marginally sited units, variable speed machine and possibly with variable pitched machines. It will also occur at wind speeds where it is difficult to obtain test results. This would include areas of pronounced hysteresis such as at cut-in or cut-out and at wind speeds that do not occur frequently such as high winds during certain seasons.

In an attempt to accommodate the inevitable problem of tests being terminated without having all bins conform to the criteria specified it is recommended that

"bins with insufficient data to conform to the standard must indicate the expected error based on the amount of data accumulated in a bin using the formula specified in CSA F417 1986 and modified as follows;

$$X = (SD)(T)/(P)(N^{.5})$$

where: X = calculated error based on 99% confidence limits

SD = Standard deviation of accumulated bin averages

T = The 'T' constant specified in CSA F417

N = The number of points in the wind speed bin

It is also recommended that for bins where it is anticipated that small amounts of data will be available (i.e. high winds) consideration be given to using one minute averages even though ten minute averages are being used for the remainder of the test.

6.5.3.3

It is recommended that the wording be changed from 'average power level for each bin may also be carried out' to 'for each bin shall also be carried out'.

6.5.5. DETERMINATION OF A.E.O.

It has been recommended that temperature corrections be applied to the power curve to ensure the season of the test does not distort the power curve and to ensure compatibility with internationally developed power curves. For Canadian applications it is proper to recognize that the climate will increase expected energy produced on an annual basis if a temperature corrected power curve is used for the projections. As an example the 500 kW Aquilo at AWTS projects an increase in annual energy output of nearly 6% if temperature is taken into account. This is significant and should be credited to any analysis being carried out. The calculation of increased output is not simple. The distribution of temperature and wind availability is a compound probability function that is not easily computed. To do so requires a point by point calculation of each variable. AWTS has done this for an Eastern Canadian location and could carry out similar calculations as required for other Canadian locales.

8.5.5.3

A simple method for estimating the increase energy yield is as follows;

$$AEC = \left(\frac{8760}{V}\right)\sum_{i=1}^{n}(Vi)P(Vi)_{\Delta}(Vi)Kt$$

where: Variables are as listed in 6.5.5 and

Kt= factor based on specific site distribution of wind and temperature.

The Kt factor can only be applied where the power curve function P(Vi) has been corrected for standard conditions which are specified. The Kt factor can then be calculated based on statistical knowledge of the Temperature and Air Density condition at the proposed site.

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